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The Effects of NUCLEAR WEAPONS

Foreword

This handbook, prepared by the Armed Forces Special Weapons Project of the Department of Defense in coordination with other cognizant government agencies and published by the United States Atomic Energy Commission, is a comprehensive summary of current knowledge on the effects of nuclear weapons. The effects information contained herein is calculated for yields up to 20 megatons and the scaling laws for hypothetically extending the calculations beyond this limit are given. The figure of 20 megatons however is not to be taken as an indication of capabilities or developments.

CHARLES E. WILSON
Secretary of Defense

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The Federal Civil Defense Administration commends this publication as the definitive source of information on the effects of nuclear weapons for the use of organizations engaged in Civil Defense activities. Its detailed treatment of the physical phenomena associated with nuclear explosions provides the necessary technical background for development of countermeasures against all nuclear effects of Civil Defense interest.

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Acknowledgment

At the request of the Atomic Energy Commission, the Armed Forces Special Weapons Project prepared this book with the assistance of the Commission. Dr. Samuel Glasstone was responsible for the compiling, writing, and editing and, largely, for its successful completion.

Assistance in the preparation and review of the book was provided by individuals associated with the Atomic Energy Commission, the Department of Defense, the Federal Civil Defense Administration, and their contractors.

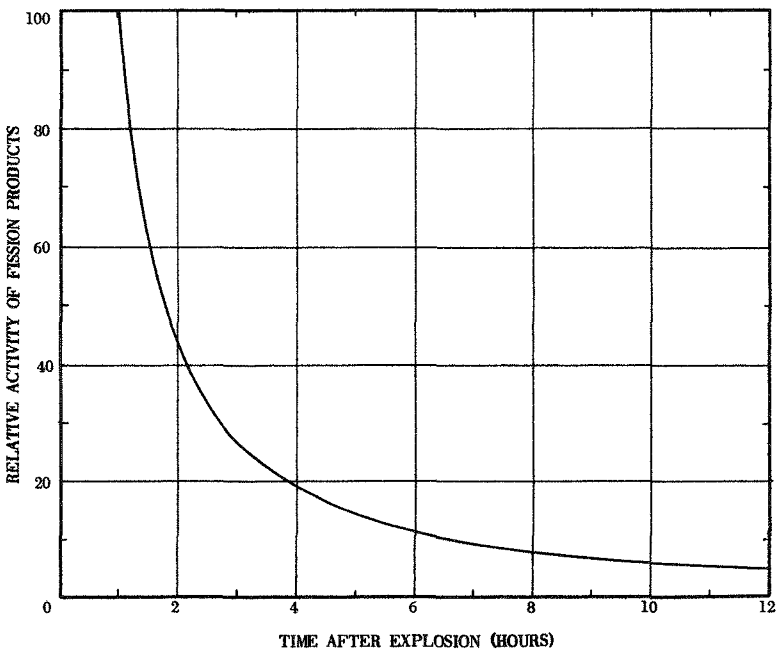

Figure 1.50. Rate of decay of fission products after a nuclear explosion (activity is taken as 100 at 1 hour after the detonation).

Alpha-Particle Activity

1.51 In addition to the beta-particle and gamma-ray activity due to the fission products, there is another kind of residual radioactivity that should be mentioned. This is the activity of the fissionable material, part of which, as noted in §1.18, remains after the explosion. Both uranium and plutonium are radioactive, and their activity consists in the emission of what are called "alpha particles". These are a form of nuclear radiation, since they are emitted from atomic nuclei; but they differ from the beta particles arising from the fission products in being much heavier and carrying a positive electrical charge. Alpha particles are, in fact, identical with the nuclei of helium atoms.

1.52 Because of their greater mass and charge, alpha particles are much less penetrating than beta particles and gamma rays of the same energy. Thus, very few alpha particles from radioactive sources can travel more than 1 to 3 inches in air before being stopped. It is doubtful whether these particles can get through the unbroken skin, and they certainly cannot penetrate clothing. Consequently, the uranium

(or plutonium) present in the bomb residues do not constitute a hazard if they are outside the body. However, if plutonium, in particular, enters the body in sufficient quantity, by ingestion, inhalation, or through skin abrasions, the effects may be serious.

Fusion (Thermonuclear) Reactions

1.53 Energy production in the sun and stars is undoubtedly due to fusion reactions involving the nuclei of various light (low atomic weight) atoms. From experiments made in laboratories with cyclotrons and similar devices, it was concluded that the fusion of isotopes of hydrogen was possible. This element is known to exist in three isotopic forms, in which the nuclei have masses of 1, 2, and 3, respectively. These are generally referred to as hydrogen (H^1), deuterium (H^2 or D^2), and tritium (H^3 or T^3). All the nuclei carry a single positive charge, i. e., they all contain one proton, but they differ in the number of neutrons. The lightest (H^1) nuclei (or protons) contain no neutrons; the deuterium (H^2) nuclei contain one neutron, and tritium (H^3) nuclei contain two neutrons.

1.54 Several different fusion reactions have been observed among the nuclei of the three hydrogen isotopes, involving either two similar or two different nuclei. In order to make these reactions occur to an appreciable extent, the nuclei must have high energies. One way in which this energy can be supplied is by means of a charged-particle accelerator, such as a cyclotron. Another possibility is to raise the temperature to very high levels. In these circumstances the fusion processes are referred to as "thermonuclear reactions," as mentioned earlier.

1.55 Four thermonuclear fusion reactions appear to be of interest for the production of energy because they are expected to occur sufficiently rapidly at realizable temperatures.[4] These are:

$$H^2+H^2=He^3+n+3.2\text{ Mev}$$
$$H^2+H^2=H^3+H^1+4\text{ Mev}$$
$$H^3+H^2=He^4+n+17\text{ Mev}$$
$$H^3+H^3=He^4+2n+11\text{ Mev},$$

where He is the symbol for helium and n (mass=1) represents a neutron. The energy liberated in each case is expressed in Mev (million electron volt) units.[5] Without going into details, it may be

[4] L. N. Ridenour, *Scientific American, 182,* No. 3, 11 (1950); H. Bethe, *ibid., 182,* No. 4, 18 (1950).

[5] An electron volt is the energy that would be acquired by a unit electric charge, i. e., an electron, if accelerated by a potential of 1 volt. The million electron volt unit, i. e., 1 Mev, is one million times as large, and is equivalent to 1.6×10^{-6} erg or 1.6×10^{-13} joule.

stated that the fission of a nucleus of uranium or plutonium, having a weight of nearly 240 atomic mass units, releases about 200 Mev. This may be compared with an average of about 24.2 Mev obtained from the fusion of 5 deuterium nuclei with a weight of 10 mass units. Weight for weight, therefore, the fusion of deuterium nuclei would produce nearly three times as much energy as the fission of uranium or plutonium.

1.56 In order to make the nuclear fusion reactions take place, temperatures of the order of a million degrees are necessary. The only known way in which such temperatures can be obtained on earth is by means of a fission explosion. Consequently, by combining a quantity of deuterium or tritium (or a mixture) with a fission bomb, it should be possible to initiate one or more of the thermonuclear fusion reactions given above. If these reactions, accompanied by energy evolution, can be propagated rapidly through a volume of the hydrogen isotope (or isotopes) a thermonuclear explosion may be realized.

1.57 It may be noted that the two reactions involving tritium (H^3) are of particular interest for several reasons. Not only do they occur more rapidly than those in which deuterium alone takes part and produce more energy, but in addition one or two neutrons are emitted in each case. These neutrons are able to contribute to the fission of uranium and plutonium, as stated in § 1.15, thus adding to the total energy release of the combined fission-fusion system.

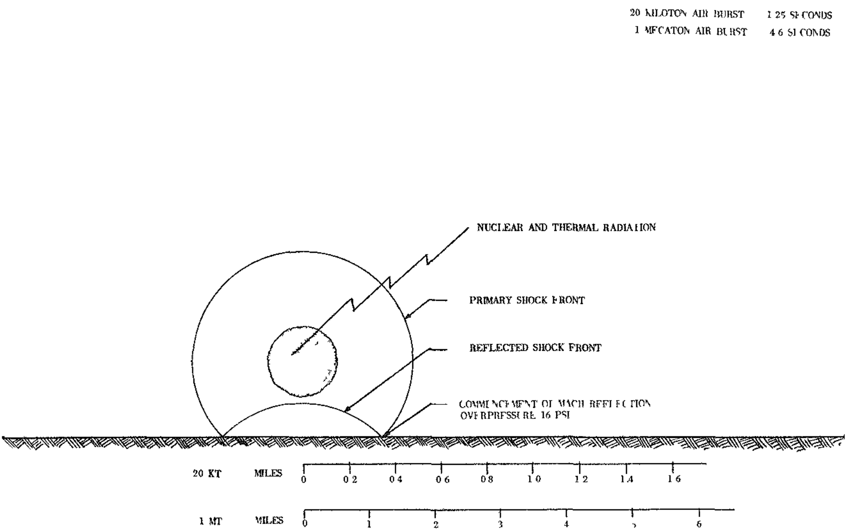

Figure 2.47b. Chronological development of an air burst: 1.25 seconds after 20-kiloton detonation; 4.6 seconds after 1-megaton detonation.

When the primary shock (or blast) wave from the explosion strikes the ground, another shock (or blast) wave is produced by reflection. At a certain distance from ground zero, which depends upon the height of burst and the energy of the bomb, the primary and reflected shock fronts fuse near the ground to form a single, reinforced Mach front (or stem).

The time and distance at which the Mach effect commences for a typical air burst are as follows:

Explosion yield	*Time after detonation (seconds)*	*Distance from ground zero (miles)*
20 kilotons	1.25	0.35
1 megaton	4.6	1.3

The overpressure at the earth's surface is then 16 pounds per square inch.

Significant quantities of thermal and nuclear radiations continue to be emitted from the ball of fire.

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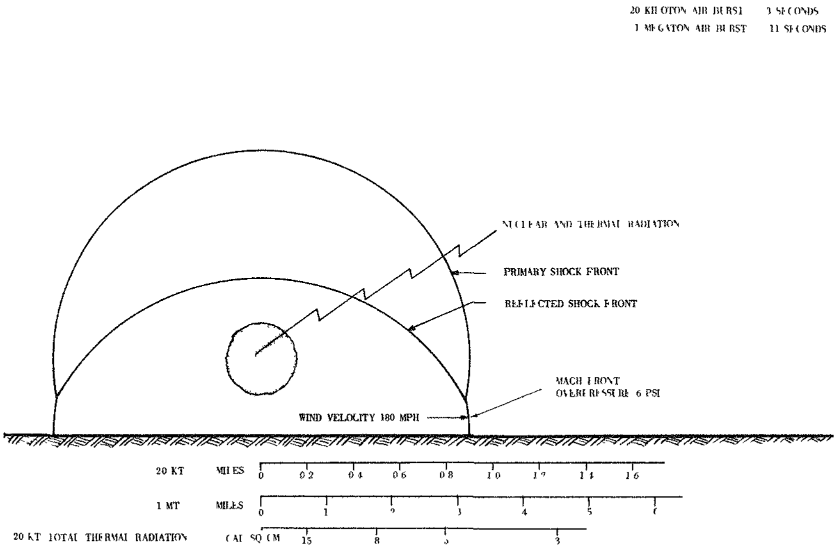

Figure 2.47c. Chronological development of an air burst: 3 seconds after 20-kiloton detonation; 11 seconds after 1-megaton detonation.

As time progresses, the Mach front (or stem) moves outward and increases in height. The distance from ground zero and the height of the stem at the times indicated are as follows:

Explosion yield	*Time after detonation (seconds)*	*Distance from ground zero (miles)*	*Height of stem (feet)*
20 kilotons	3	0.87	185
1 megaton	11	3.2	680

The overpressure at the Mach front is 6 pounds per square inch and the blast wind velocity immediately behind the front is about 180 miles per hour.

Nuclear radiations still continue to reach the ground in significant amounts. But after 3 seconds from the detonation of a 20-kiloton bomb, the fireball, although still very hot, has cooled to such an extent that the thermal radiation is no longer important. The total accumulated amounts of thermal radiation, expressed in calories per square centimeter, received at various distances from ground zero after a 20-kiloton air burst, are shown on the scale at the bottom of the figure (for further details, see Chapter VII). Appreciable amounts of thermal radiation still continue to be emitted from the fireball at 11 seconds after a 1-megaton explosion; the thermal radiation emission is spread over a longer time interval than for an explosion of lower energy yield.

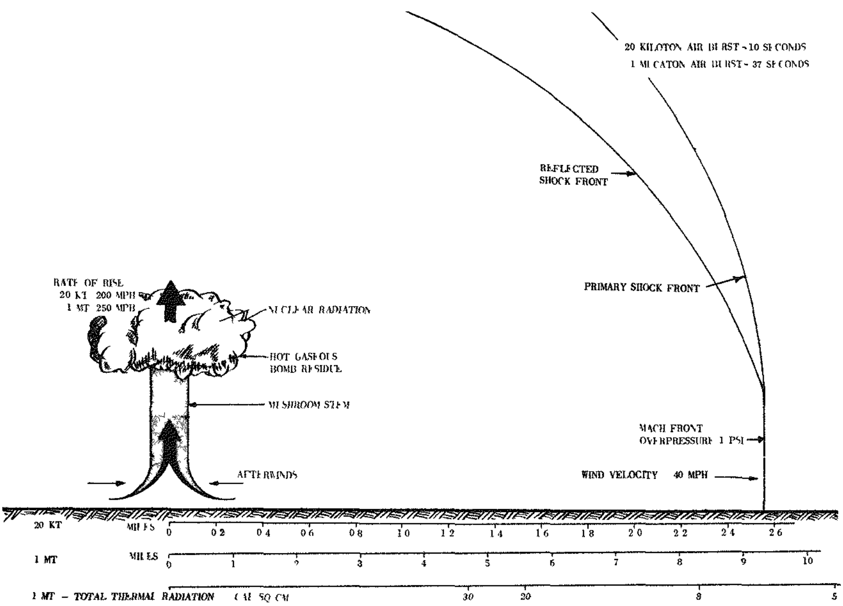

Figure 2.47d. Chronological development of an air burst: 10 seconds after 20-kiloton detonation; 37 seconds after 1-megaton detonation.

At 10 seconds after a 20-kiloton explosion the Mach front is over 2½ miles from ground zero, and 37 seconds after a 1-megaton detonation it is nearly 9½ miles from ground zero. The overpressure at the front is roughly 1 pound per square inch, in both cases, and the wind velocity behind the front is 40 miles per hour. Apart from plaster damage and window breakage, the destructive effect of the blast wave is essentially over. Thermal radiation is no longer important, even for the 1-megaton burst, the total accumulated amounts of this radiation, at various distances, being indicated on the scale at the bottom of the figure. Nuclear radiation, however, can still reach the ground to an appreciable extent; this consists mainly of gamma rays from the fission products.

The ball of fire is no longer luminous, but it is still very hot and it behaves like a hot-air balloon, rising at a rapid rate. As it ascends, it causes air to be drawn inward and upward, somewhat similar to the updraft of a chimney. This produces strong air currents, called afterwinds, which raise dirt and debris from the earth's surface to form the stem of what will eventually be the characteristic mushroom cloud.

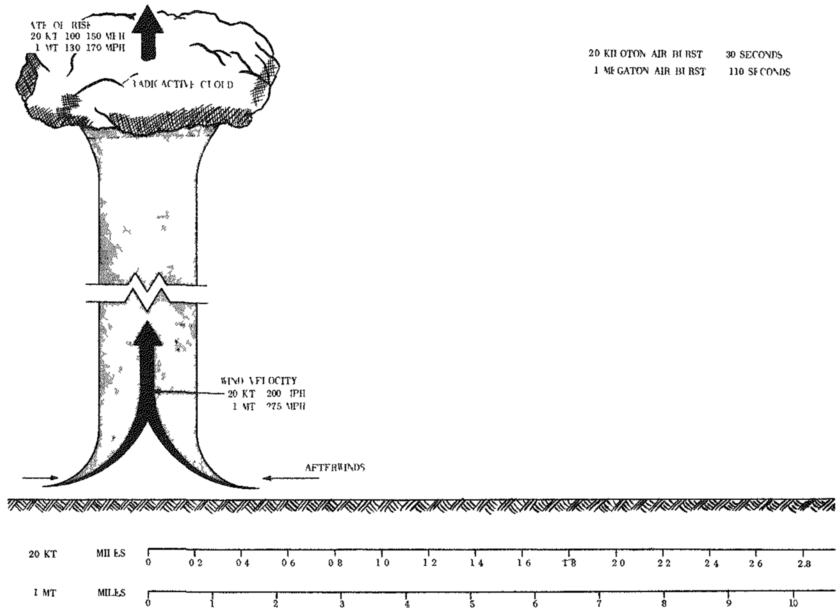

Figure 2.47e. Chronological development of an air burst: 30 seconds after 20-kiloton detonation; 110 seconds after 1-megaton detonation.

The hot residue of the bomb continues to rise and at the same time it expands and cools. As a result, the vaporized fission products and other bomb residues condense to form a cloud of highly radioactive particles. The afterwinds, having velocities of 200 or more miles per hour, continue to raise a column of dirt and debris which will later join with the radioactive cloud to form the characteristic mushroom shape. At the times indicated, the cloud from a 20-kiloton explosion will have risen about 1½ miles and that from a 1-megaton explosion about 7 miles. Within about 10 minutes, the bottom of the mushroom head will have attained an altitude of 5 to 15 miles, according to the energy yield of the explosion. The top of the cloud will rise even higher. Ultimately, the particles in the cloud will be dispersed by the wind, and, except under weather conditions involving precipitation, there will be no appreciable local fallout.

Although the atomic cloud is still highly radioactive, very little of the nuclear radiation reaches the ground. This is the case because of the increased distance of the cloud above the earth's surface and the decrease in the activity of the fission products due to natural radioactive decay.

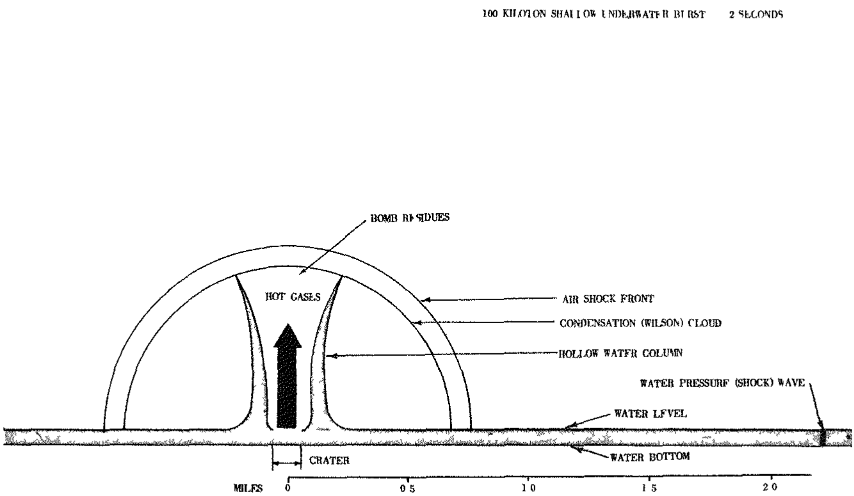

Figure 2.66a. Chronological development of a 100-kiloton shallow underwater burst: 2 seconds after detonation.

When a nuclear bomb is exploded under the surface of water, a bubble of intensely hot gases is formed which will burst through the surface if the detonation occurs at a shallow depth. As a result, a hollow column of water and spray is shot upward, reaching a height of over 5,000 feet in 2 seconds after a 100-kiloton explosion. The gaseous bomb residues are then vented through the hollow central portion of the water column.

The shock (or pressure) wave produced in the water by the explosion travels outward at high speed, so that at the end of 2 seconds it is more than 2 miles from surface zero. The expansion of the hot gas bubble also results in the formation of a shock (or blast) wave in the air, but this moves less rapidly than the shock wave in water, so that the front is some 0.8 mile from surface zero.

Soon after the air shock wave has passed, a dome-shaped cloud of condensed water droplets, called the condensation cloud, is formed for a second or two. Although this phenomenon is of scientific interest, it has apparently no significance as far as nuclear attack or defense is concerned.

For an underwater burst at moderate (or great) depth, essentially all of the thermal radiation and much of the initial nuclear radiation is absorbed by the water.

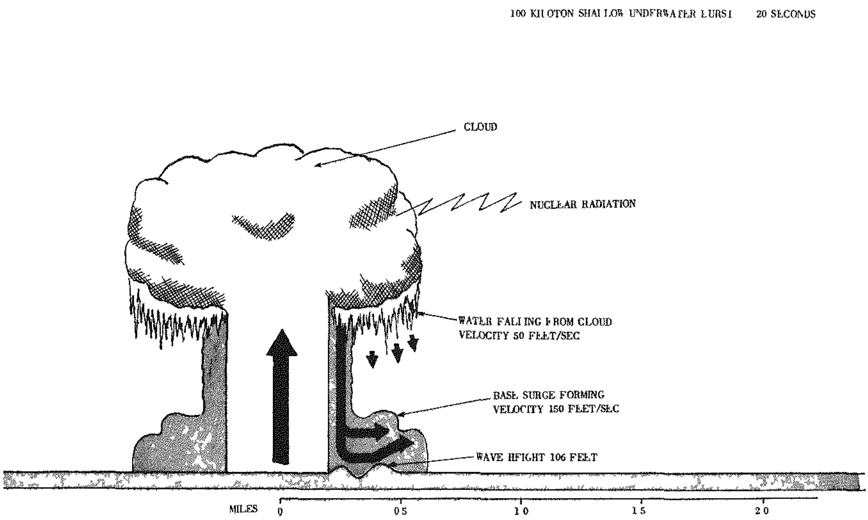

Figure 2.66c. Chronological development of a 100-kiloton shallow underwater burst: 20 seconds after detonation.

As the water and spray forming the column continue to descend, the base surge cloud develops, billowing upward and moving outward across the surface of the water. At 20 seconds after the 100-kiloton explosion the height of the base surge is about 1,000 feet and its front is nearly ½ mile from surface zero. It is then progressing outward at a rate of approximately 150 feet per second (100 miles per hour).

At about this time, large quantities of water, sometimes referred to as the massive water fallout, begin to descend from the atomic cloud. The initial rate of fall is about 50 feet per second. Because of the loss of water from the column, in one way or another, its diameter has now decreased to 2,000 feet.

By the end of 20 seconds, the first water wave has reached about 2,000 feet (0.38 mile) from surface zero and its height is roughly 106 feet.

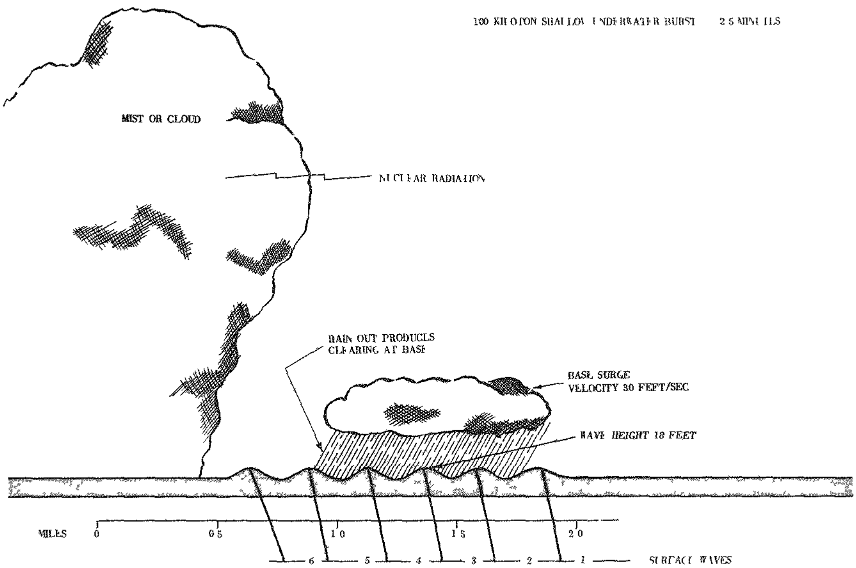

Figure 2.66e. **Chronological development of a 100-kiloton shallow underwater burst: 2.5 minutes after detonation.**

By 2½ minutes after the 100-kiloton underwater explosion, the front of the base surge is nearly 2 miles from ground zero and its height is roughly 2,000 feet. The greatest effective spread of the base surge cloud, reached in 4 minutes, is approximately 2½ miles from surface zero, i. e., 5 miles across. The base surge now appears to be rising from the surface of the water. This effect is attributed to several factors, including an actual increase in altitude, thinning of the cloud by engulfing air, and raining out of the larger drops of water. Owing to natural radioactive decay of the fission products, to rainout, and to dilution of the mist by air, the intensity of the nuclear radiation from the base surge at 2½ minutes after the explosion is only one-twentieth of that at 1 minute.

The descent of water and spray from the column and from condensation in the atomic cloud results in the formation of a continuous mass of mist or cloud down to the surface of the water. Ultimately, this merges with the base surge, which has spread and increased in height, and also with the natural clouds of the sky, to be finally dispersed by the wind.

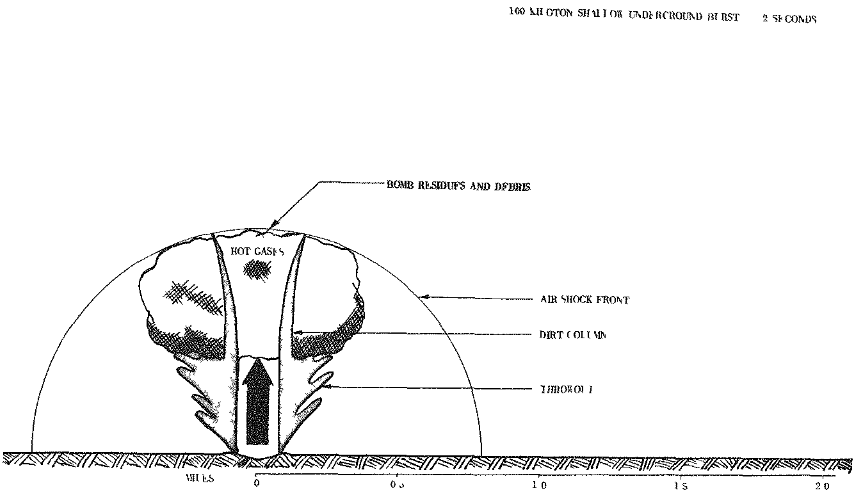

Figure 2.75a. Chronological development of a 100-kiloton shallow underground burst: 2.0 seconds after detonation.

When a nuclear explosion occurs at a shallow depth underground, the ball of fire breaks through the surface of the earth within a fraction of a second of the instant of detonation. As the fireball penetrates the surface, the intensely hot gases at high pressure are released and they carry up with them into the air large quantities of soil, rock, and debris in the form of a hollow column. For a burst at a shallow depth, the column tends to assume the shape of an inverted cone which fans out as it rises to produce a radial throw-out. A highly radioactive cloud, which contains large quantities of earth, is formed above the throw-out as the hot vapors cool and condense. Because of the mass displacement of material from the earth's surface, a crater is formed. For a 100-kiloton bomb exploding 50 feet beneath the surface of dry soil, the crater would be about 120 feet deep and 720 feet across. The weight of the material removed would be over a million tons.

In addition to the shock (or pressure) wave in the ground, somewhat related to an earthquake wave, the explosion is accompanied by a shock (or blast) wave in the air. At 2 seconds after the explosion, the shock front in air is about ¾ mile from surface zero.

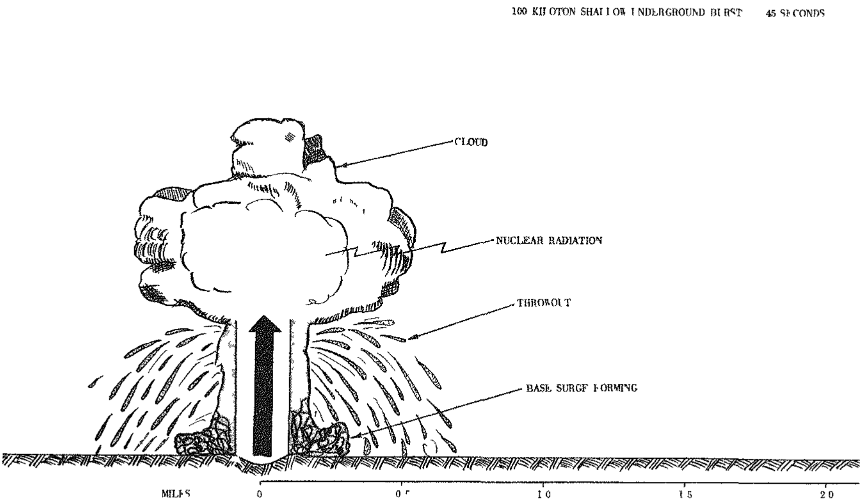

Figure 2.75c. Chronological development of a 100-kiloton shallow underground burst: 45 seconds after detonation.

As the material from the column descends, the finer soil particles attain a high velocity and upon reaching the ground they spread out rapidly to form a base surge similar to that in an underwater explosion. The extent of the base surge, which is likely to be radioactive, depends upon many factors, including the energy yield of the explosion, the depth of burst, and the nature of the soil. It is believed that a dry sandy terrain will be particularly conducive to base surge formation.

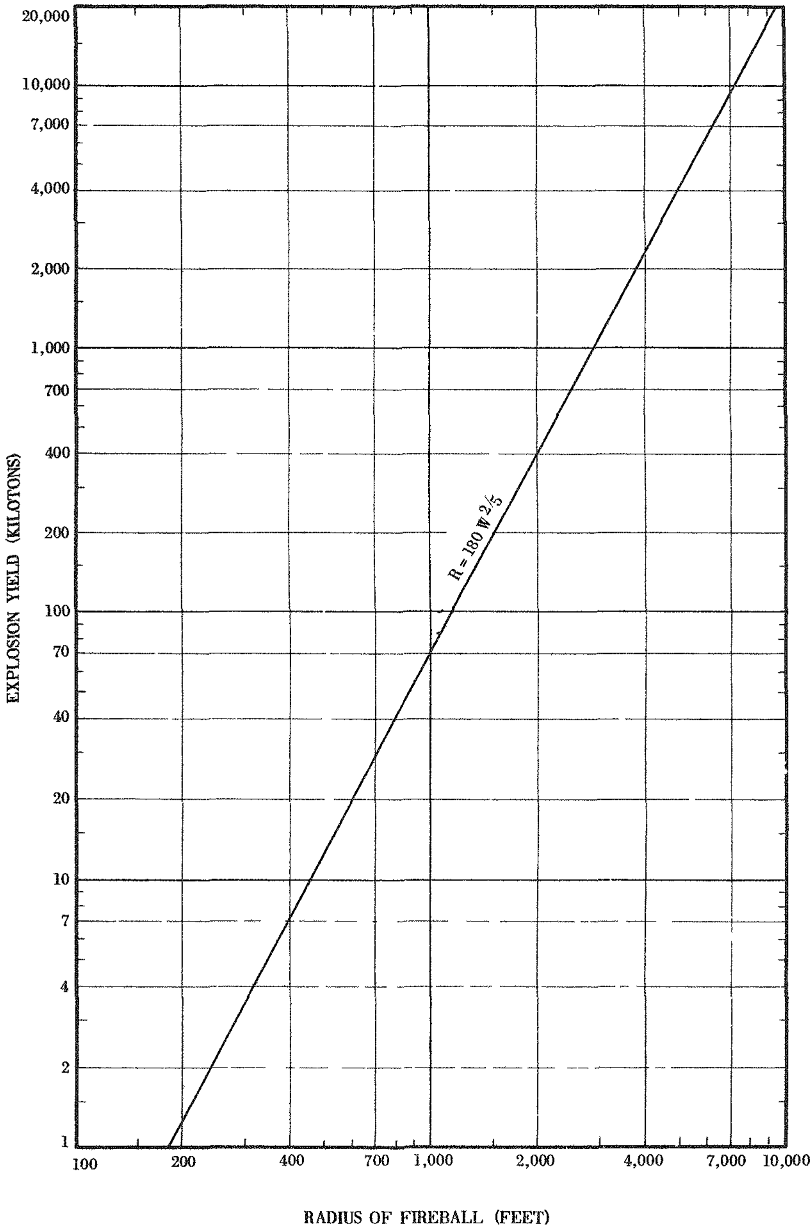

Figure 2.88. Fireball radius for local fallout.

natural store of energy from the path it might otherwise have followed.

2.95 The addition of energy to the atmosphere does not appear to be an important factor since the amount of energy released in a nuclear explosion is not large in comparison with that associated with most meteorological phenomena. Further, it is not produced in a manner that is likely to be conducive to weather changes. There is a possibility that the atmosphere may be in an unstable state, and so the sudden impulse of a nuclear explosion might cause a change in the weather that would otherwise not take place. As far as thunderstorm formation is concerned, it is believed that the release of energy in a nuclear explosion is so rapid that the atmospheric conditions could not be rearranged within the limited time, to take advantage of the extra energy.

2.96 There are three ways, which appear reasonable, whereby the products of a nuclear explosion might indirectly, e. g., by trigger action, produce changes in the weather. These are (1) the debris thrown into the air by the explosion may have an effect in seeding (nucleating) existing clouds, thus changing the pattern of cloudiness or precipitation over large areas; (2) the radioactive nature of the bomb residues will change the electrical conductivity of the air and this may have an influence on observable meteorological phenomena; and (3) the debris entering the stratosphere may interfere with the transmission of radiant energy from the sun and so serve to decrease the temperature of the earth. These possibilities will be considered in turn.

2.97 Although the techniques for testing seeding efficiency are not too well developed and are being given further study, the evidence obtained so far indicates that bomb debris is not effective as a cloud-seeding agent. It is true that rain fell after the nuclear explosion over Hiroshima in August 1945, but it seems certain that this was largely, if indirectly, due to widespread fires which sustained convection for several hours after the detonation had occurred. A similar phenomenon has been observed, under suitable air mass conditions, as a result of a "fire storm" over large forest fires and over burning cities during World War II. However, there has been no analogous effect in connection with the numerous explosions of nuclear test devices, since these were not accompanied by large fires.

2.98 Within two or three hours after the Bikini ABLE (air) burst in 1946, light rain showers developed throughout the northern Marshall Islands. Some attempt was made to relate the formation of the showers to the atomic cloud. But the showers were very widespread and were readily explained on the basis of the existing meteoro-

logical conditions. The records show that the only detectable changes which occurred in the wind or atmospheric structure were the momentary effects of the blast and thermal radiation. In any event, such changes were significant only in the immediate vicinity of the burst. The main cloud pattern over the lagoon was unchanged apart from the atomic cloud directly associated with the explosion.

2.99 The amount of ionization produced by the radioactive material, even for a high-energy nuclear explosion, is believed to be insufficient to have any significant effect on general atmospheric conditions. It appears improbable, therefore, that the ionization accompanying a nuclear explosion can affect the weather.

2.100 The dust raised in severe volcanic eruptions, such as that at Krakatao in 1883, is known to cause a noticeable reduction in the sunlight reaching the earth, but it has not been established that this decrease has any great effect on the weather. The amount of debris remaining in the atmosphere after the explosion of even the largest nuclear weapons is probably not more than about 1 percent or so of that raised by the Krakatao eruption. Further, solar radiation records reveal that none of the nuclear explosions to date has resulted in any detectable change in the direct sunlight recorded on the ground.

2.101 The variability of weather phenomena due to natural causes makes it difficult to prove (or disprove) that any change in the weather following a nuclear explosion was due to the detonation. However, the general opinion of competent meteorologists, both in the United States and in other countries, is that, apart from localized effects in the vicinity of the test area, there has been no known influence of nuclear explosions on the weather.

DUCTILITY

3.73 The term ductility refers to the ability of a material or structure to absorb energy inelastically without failure; in other words, the greater the ductility, the greater the resistance to failure. Materials which are brittle have poor ductility and fail easily.

3.74 There are two main aspects of ductility to be considered. When a force (or load) is applied to a material so as to deform it, as is the case in a nuclear explosion, for example, the initial deformation is said to be "elastic." Provided it is still in the elastic range, the material will recover its original form when the loading is removed. However, if the "stress" produced by the load is sufficiently great, the material passes into the "plastic" range. In this state the material does not recover completely after removal of the stress, that is to say, the deformation is permanent, but there is no failure. Only when the stress reaches the "ultimate strength" does failure, i. e., breakage, occur.

3.75 Ideally, a structure which is to suffer little damage from blast should have as much elasticity as possible. Unfortunately, structural materials are generally not able to absorb much energy in the elastic range, although many common materials can take up large amounts of energy in the plastic range before they fail. The problem in blast-resistant design, therefore, is to decide how much permanent (plastic) deformation can be accepted before a particular structure is rendered useless. This will, of course, vary with the nature and purpose of the structure. Although deformation to the point of collapse is definitely undesirable, some lesser deformation may not seriously interfere with the continued use of the structure.

3.76 It is evident that ductility is a desirable property of structural materials required to resist blast. Structural steel and steel reinforcement have this property to a considerable extent. They are able to absorb large amounts of energy, e. g., from a blast wave, without failure and thus reduce the chances of collapse of the structure in which they are used. Steel has the further advantage of a higher yield point (or elastic limit) under dynamic than under static loading.

3.77 Although concrete alone is not ductile, when steel and concrete are used together, as in reinforced-concrete structures, the ductile behavior of the steel will usually predominate. The structure will then have considerable ductility and, consequently, resistance to blast. Without reinforcement, masonry walls are completely lacking in ductility and readily suffer brittle failure, as stated above.

TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA[5]

PROPERTIES OF BLAST WAVE AT SURFACE

3.78 The characteristics of the blast wave have been discussed in a qualitative manner in the earlier parts of this chapter, and the remaining sections will be devoted to a consideration of some of the quantitative aspects of blast wave phenomena in air.[6] The basic relationships among the properties of a blast wave, having a sharp front at which there is a sudden pressure discontinuity, are derived from the Rankine-Hugoniot conditions based on the conservation of mass, energy, and momentum at the shock front. These conditions, together with the equation of state for air, permit the derivation of the required relations involving the shock velocity, the particle (or wind) velocity, the overpressure, the dynamic pressure, and the density of the air behind the ideal shock front.

3.79 The blast wave properties in the region of regular reflection are somewhat complex and depend on the angle of incidence of the wave with the ground and the shock strength. For a contact surface burst, when there is but a single hemispherical (fused) wave, as stated in § 3.29, and in the Mach region below the triple point path for an air burst, the various blast wave characteristics at the shock front are uniquely related by the Rankine-Hugoniot equations. It is for these conditions, in which there is a single shock front, that the following results are applicable.

3.80 The shock velocity, U, and the particle velocity (or peak wind velocity behind the shock front), u, are expressed by

$$U=c_0(1+6p/7P_0)^{1/2}$$

and

$$u=\frac{5p}{7P_0}\cdot\frac{c_0}{(1+6p/7P_0)^{1/2}},$$

where p is the peak overpressure (behind the shock front), P_0 is the ambient pressure (ahead of the shock), and c_0 is the ambient sound velocity (ahead of the shock). The density, ρ, of the air behind the shock front is related to the ambient density, ρ_0, by

$$\frac{\rho}{\rho_0}=\frac{7+6p/P_0}{7+p/P_0}.$$

[5] The remaining sections of this chapter may be omitted without loss of continuity.

[6] The technical aspects of blast loading and response of structures, and other related topics, are treated in Chapter VI.

The dynamic pressure, q, is defined by

$$q=\tfrac{1}{2}\rho u^2,$$

and the introduction of the appropriate Rankine-Hugoniot equations leads to

$$q=\frac{5}{2}\cdot\frac{p^2}{7P_0+p}$$

for the peak dynamic pressure. The variations of shock velocity, particle (or peak wind) velocity, and dynamic pressure with the peak overpressure at sea level, as derived from the foregoing equations, are shown graphically in Fig. 3.80.

3.81 When the blast wave strikes a surface, such as that of a structure, at normal incidence, i. e., head on, the instantaneous value of the reflected overpressure, p_r is given by

$$p_r=2p\left(\frac{7P_0+4p}{7P_0+p}\right). \tag{3.81.1}$$

It can be seen from this expression that the value of p_r approaches $8p$ for large values of the incident overpressure (strong shocks) and tends toward $2p$ for small overpressures (weak shocks). A curve showing the variation of the instantaneous reflected pressure with the peak incident overpressure is included in Fig. 3.80.

3.82 The equations in § 3.80 give the peak values of the various blast wave parameters at the shock front. As seen earlier, however, the overpressure and dynamic pressure both decrease with time, although at different rates. For many situations, the variation of the overpressure behind the shock front with time at a given point can be represented by the simple empirical equation

$$p(t)=p\left(1-\frac{t}{t_+}\right)e^{-t/t_+}, \tag{3.82.1}$$

where $p(t)$ is the overpressure at any time, t, after the arrival of the shock front, p is the peak overpressure, and t_+ is the duration of the positive phase of the blast wave. This expression is represented graphically in Fig. 3.82, in which the "normalized" overpressure, i. e., the value relative to the peak overpressure, is plotted against the "normalized" time, i. e., the time relative to the duration of the positive phase. It may be noted that in the event of the interaction of the blast wave with a structure, this equation is used in determining the air blast loading.

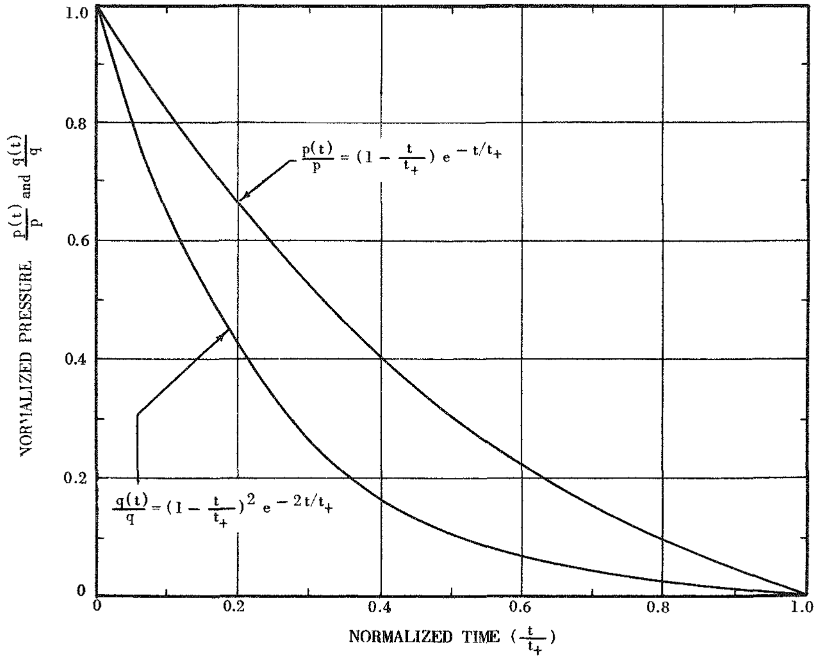

Figure 3.82. Normalized overpressure and dynamic pressure versus normalized time.

3.83 A similar empirical expression for the variation of the dynamic pressure with time behind the shock front is

$$q(t)=q\left(1-\frac{t}{t_+}\right)^2 e^{-2t/t_+},$$

where $q(t)$ is the value of the dynamic pressure at any time, t, after the arrival of the shock front, and q is the peak dynamic pressure. A plot of this equation is also shown in Fig. 3.82.

3.84 Another important blast damage parameter is the "impulse," which takes into account the duration of the positive phase and the variation of the overpressure during that time. Impulse may be defined as the total area under the overpressure-time curve, such as that shown in Fig. 3.82, at a given location. The positive phase overpressure impulse, I, (per unit area) may then be represented mathematically by

$$I=\int_0^{t_+} p(t)dt,$$

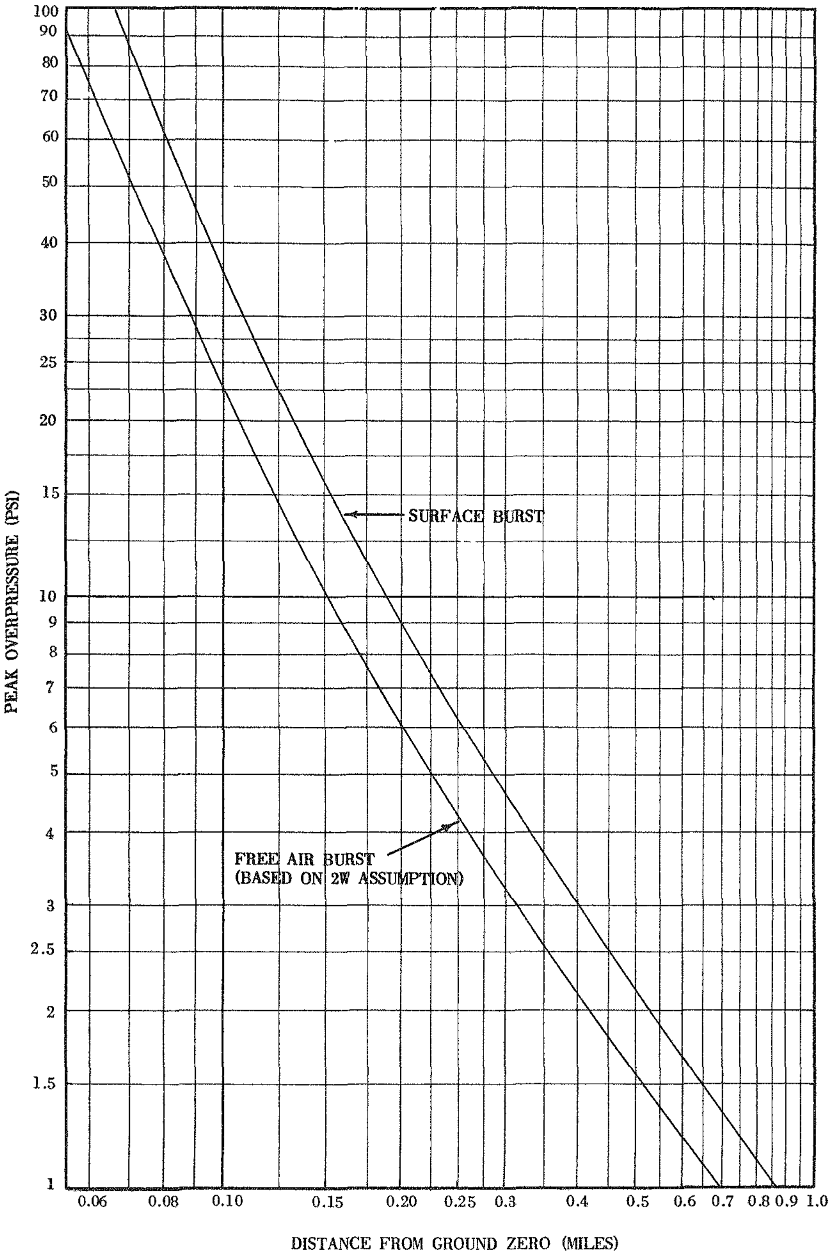

Figure 3.94a. Peak overpressure for a 1-kiloton surface burst and free air burst.

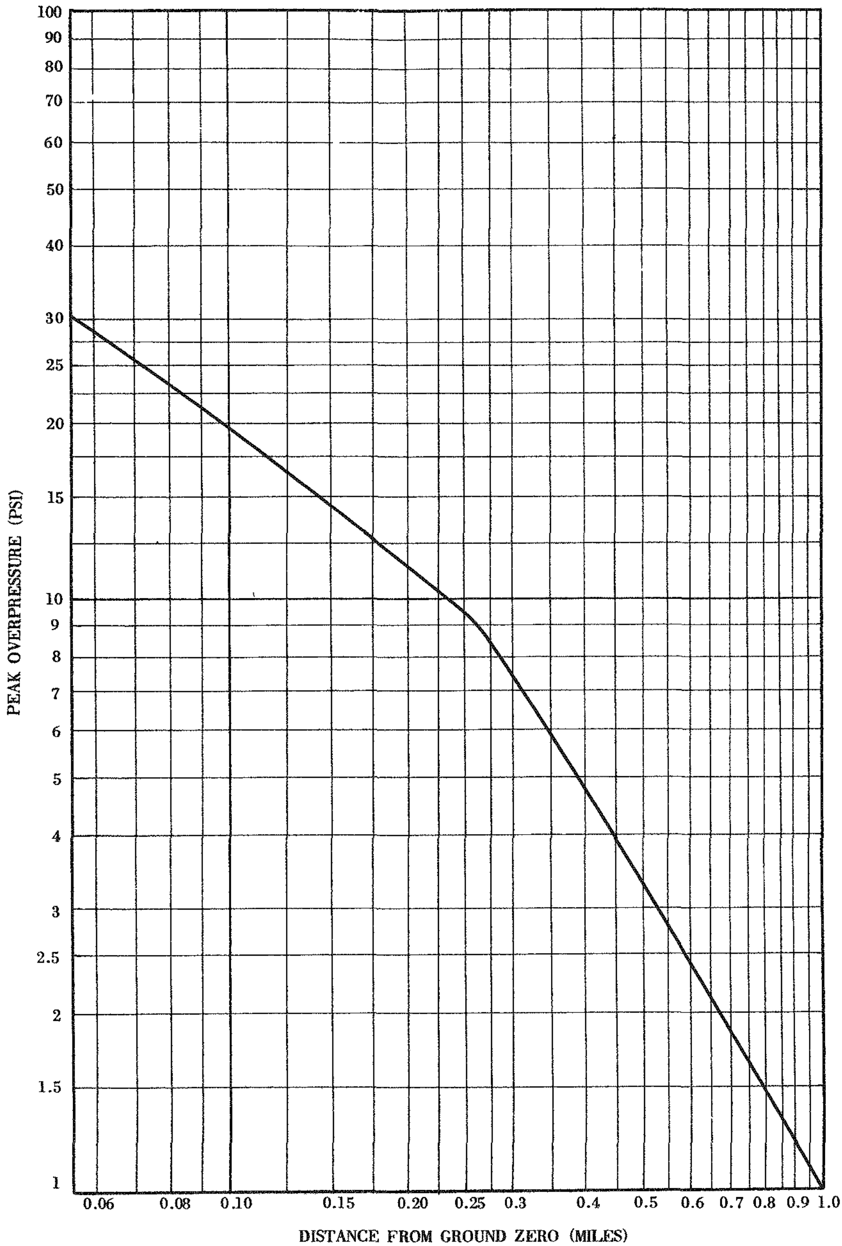

Figure 3.94b. Peak overpressure on the surface for a 1-kiloton typical air burst.

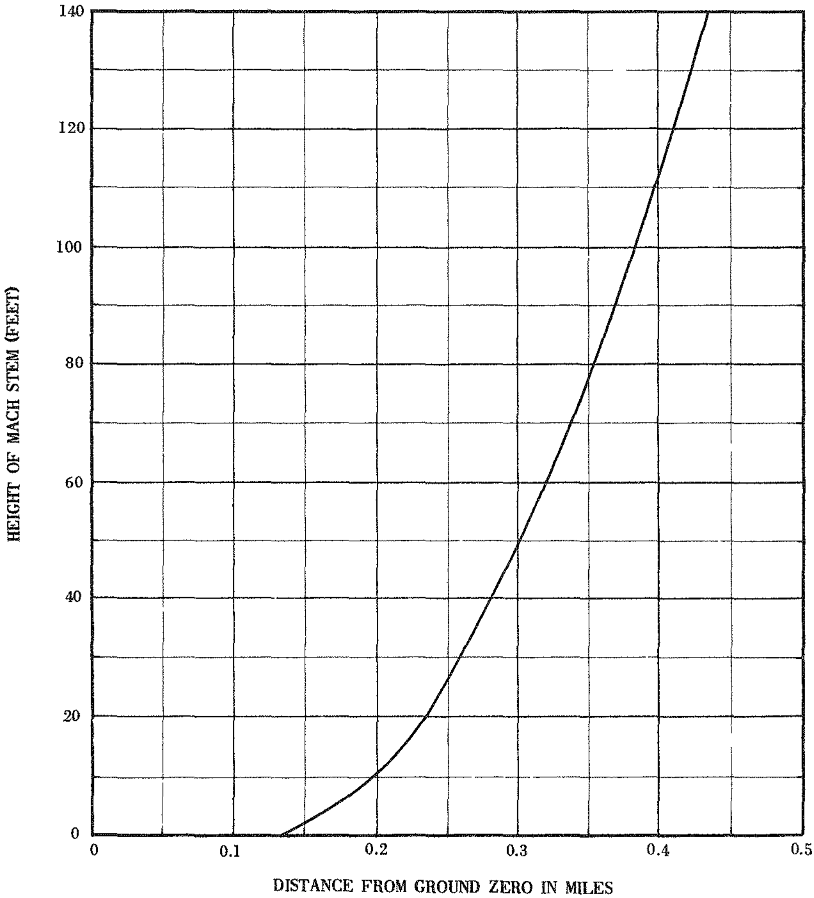

Figure 3.94c. Height of Mach stem (path of triple point) for a 1-kiloton air burst.

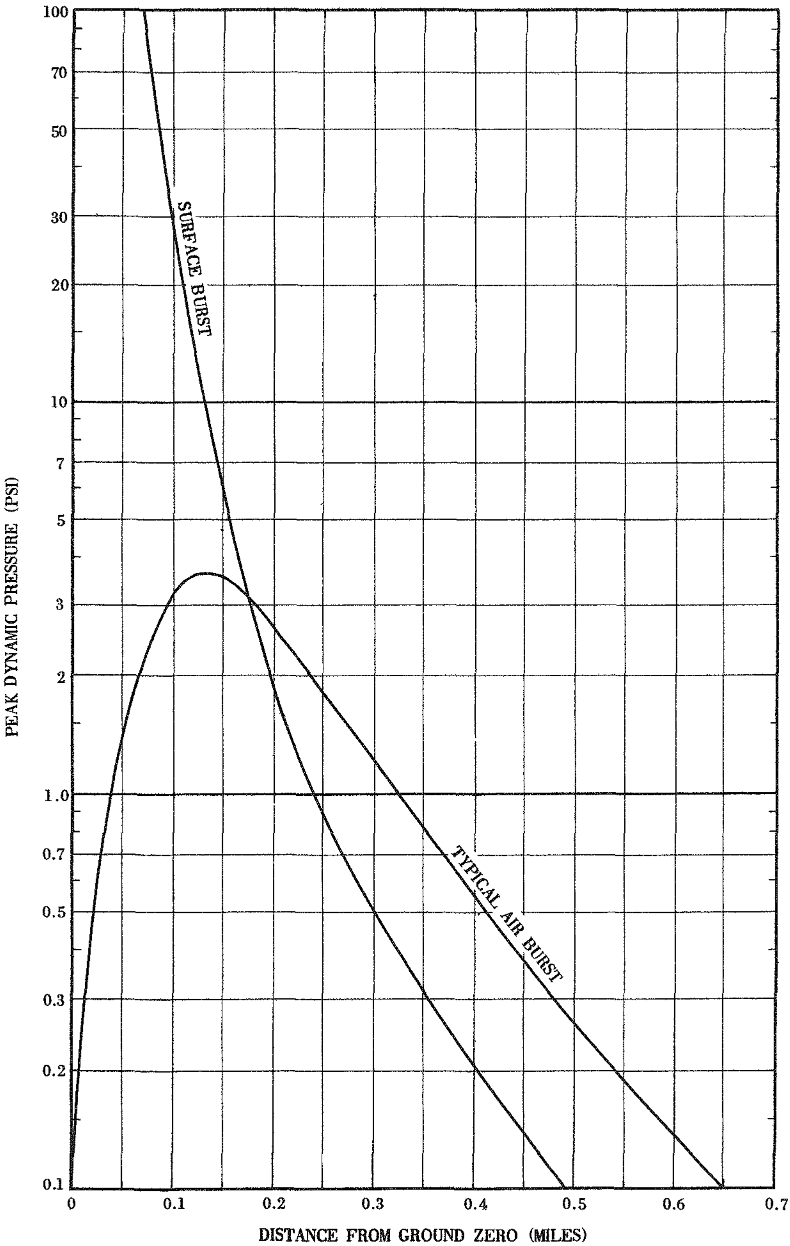

Figure 3.95. Horizontal component of peak dynamic pressure for a 1-kiloton explosion.

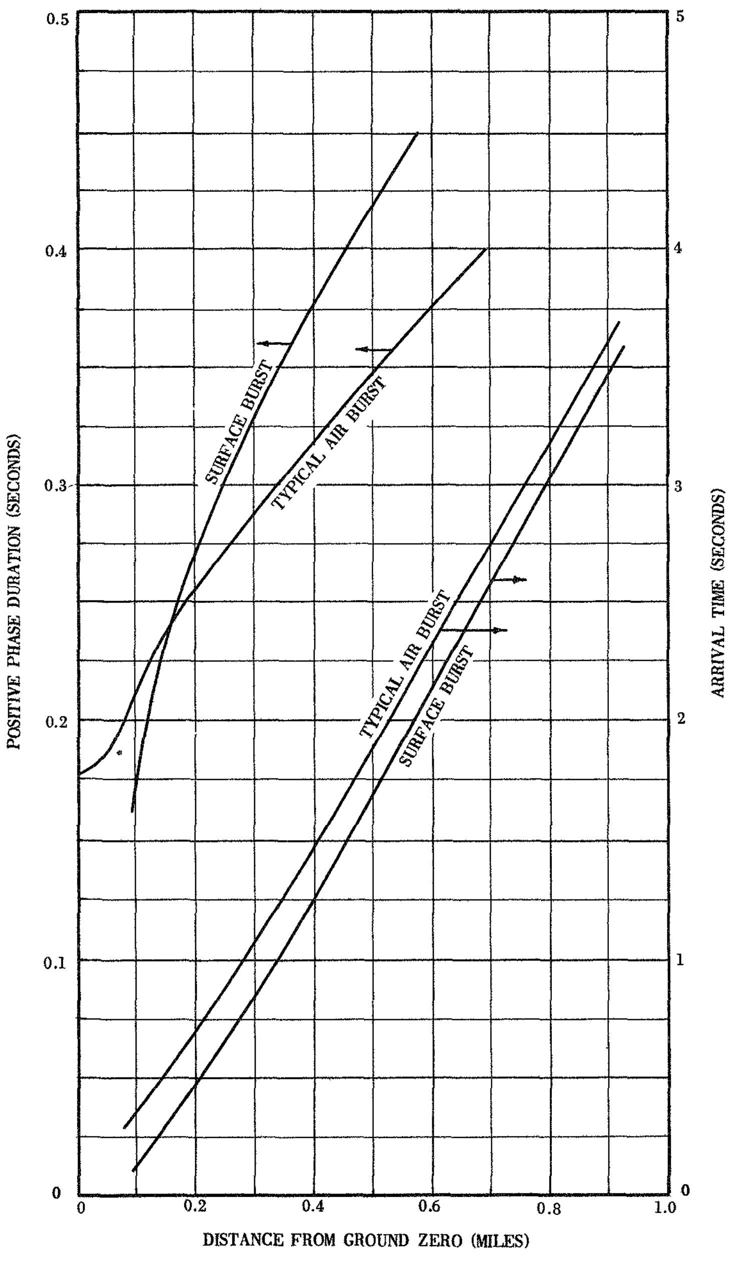

Figure 3.96. Times of arrival and positive phase durations at the surface for a 1-kiloton explosion.

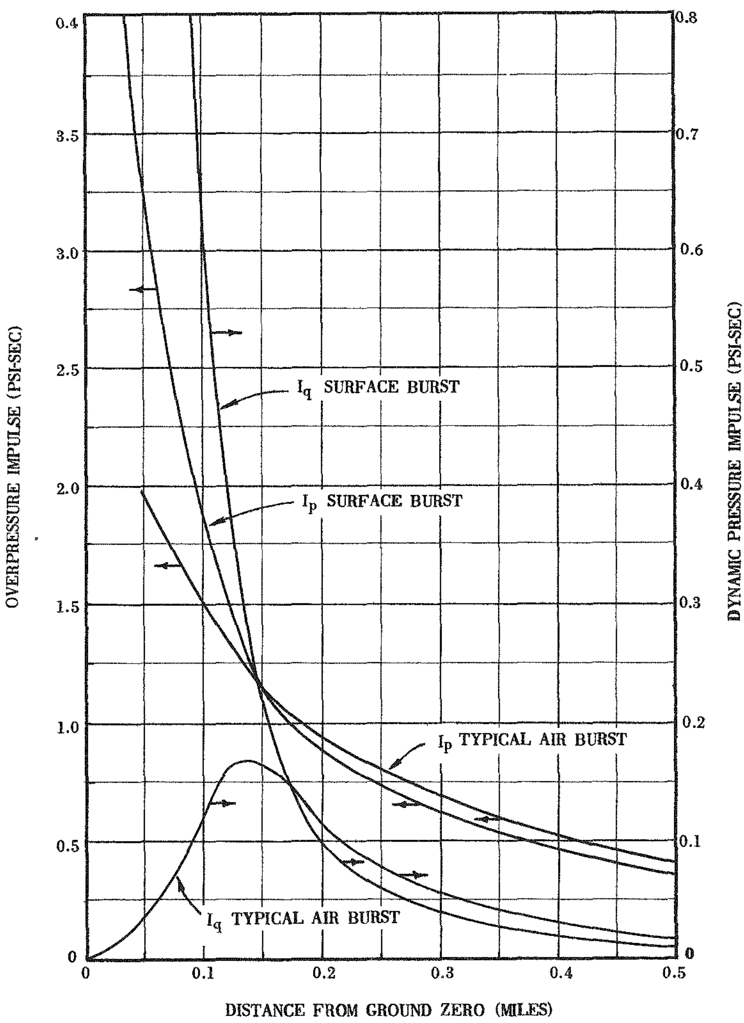

Figure 3.97. Overpressure and dynamic pressure positive phase impulse for a 1-kiloton explosion.

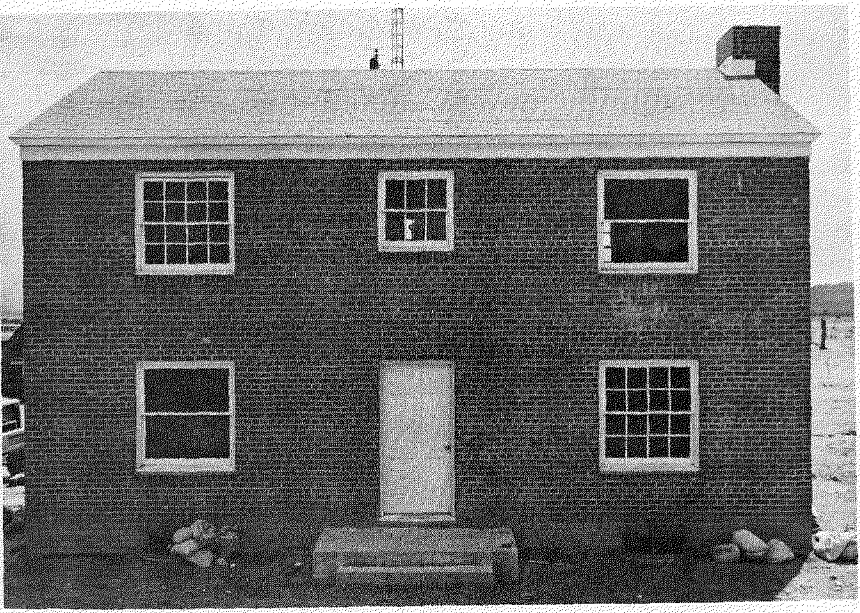

Figure 4.29. Unreinforced brick house before a nuclear explosion, Nevada Test Site.

Figure 4.30. Unreinforced brick house after the nuclear explosion (5 psi overpressure).

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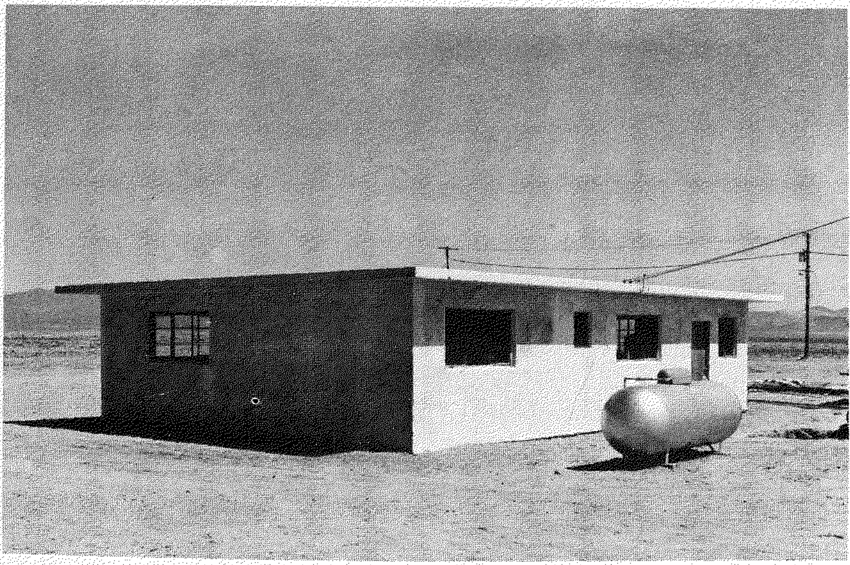

Figure 4.37. Reinforced precast concrete house before a nuclear explosion, Nevada Test Site.

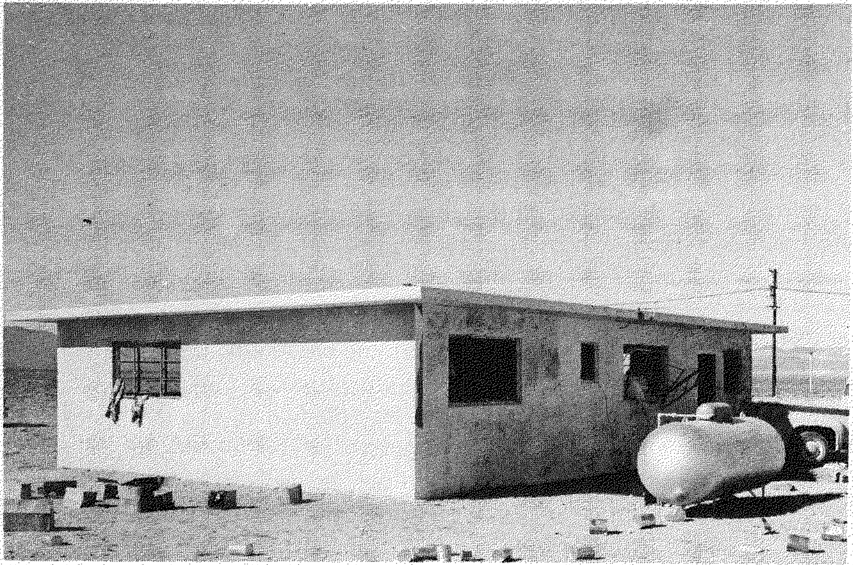

Figure 4.38. Reinforced precast concrete house after the nuclear explosion (5 psi overpressure). The LP-gas tank, sheltered by the house, is essentially undamaged.

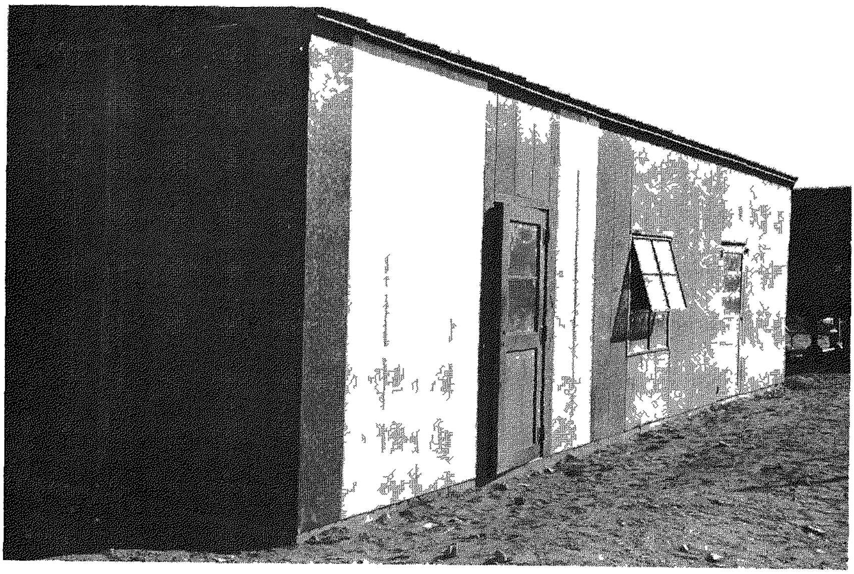

Figure 4.66a Exterior of self-framing steel panel building before a nuclear explosion, Nevada Test Site.

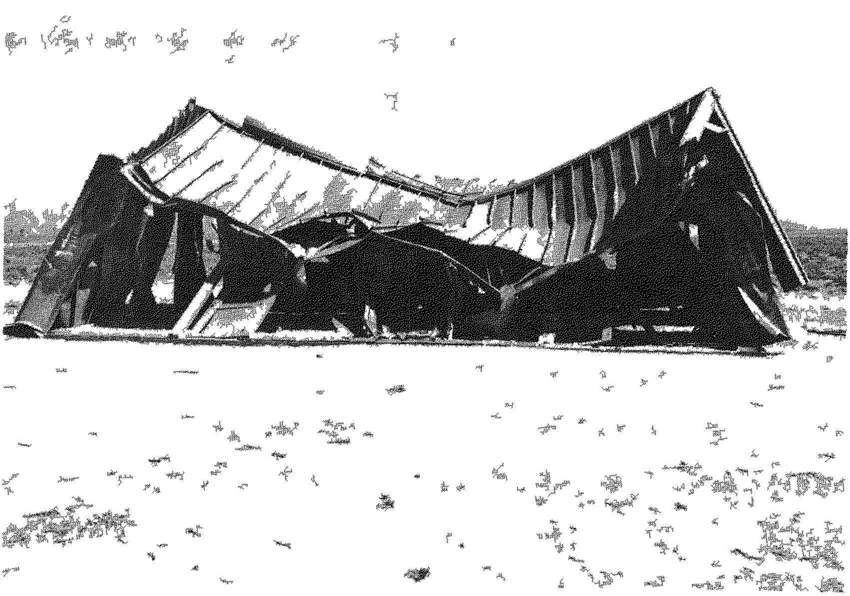

Figure 4.66b Self-framing steel panel building after the nuclear explosion (3 1 psi overpressure).

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Figure 4.75. Machine tools behind masonry wall before a nuclear explosion, Nevada Test Site.

Figure 4.76a. Machine tools after the nuclear explosion (10 psi overpressure).

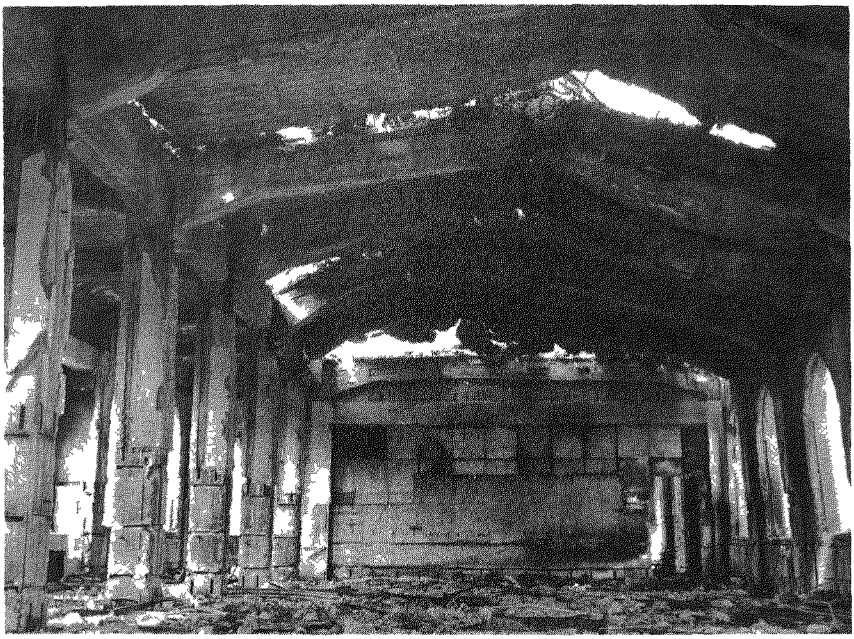

Figure 4 85a Buckling and cracking of beams in reinforced-concrete building (0 32 mile from ground zero at Nagasaki).

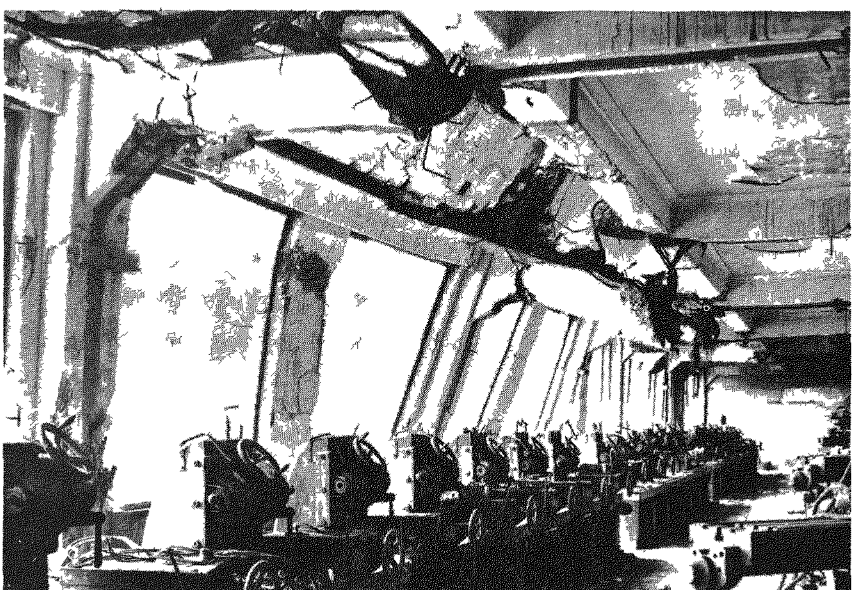

Figure 4 85b Multistory reinforced concrete frame building showing the failure of columns and girders (0 36 mile from ground zero at Nagasaki)

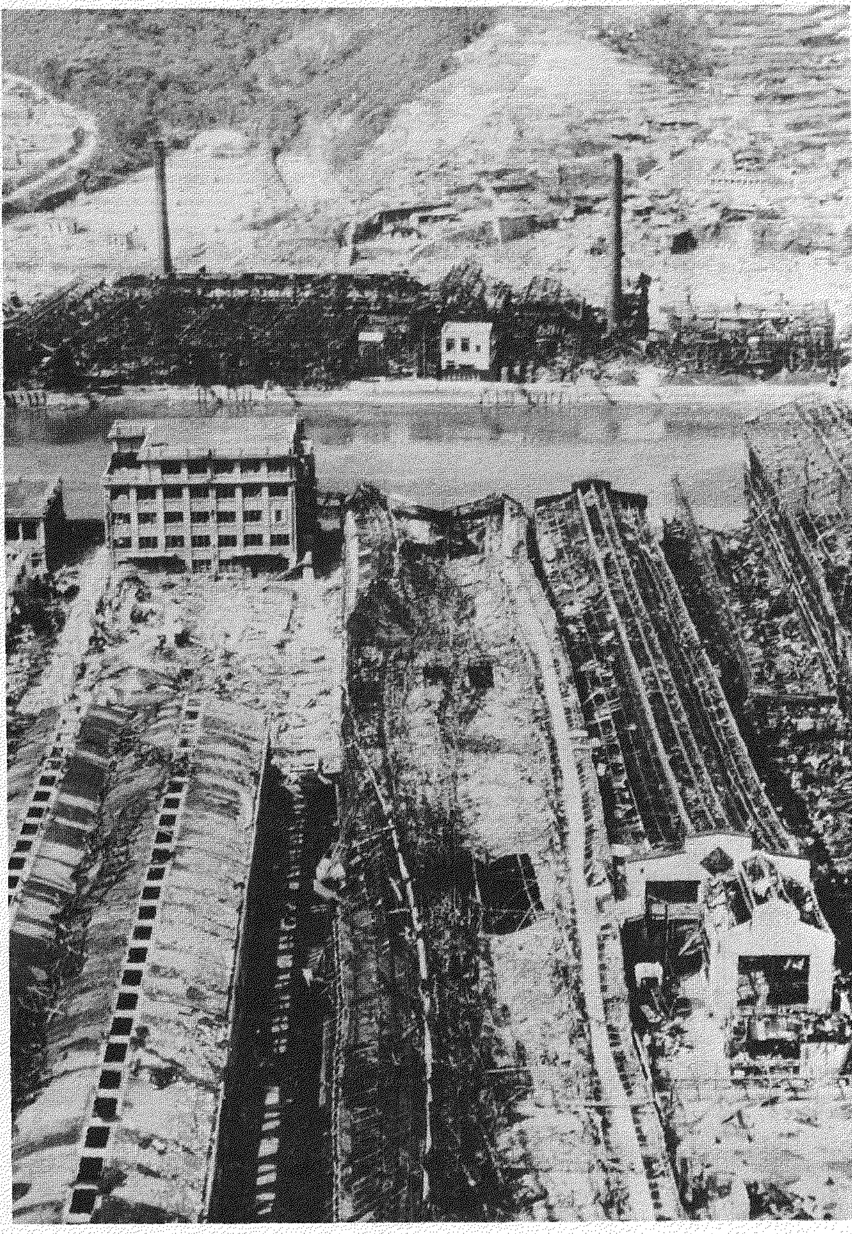

Figure 4.87. At left and back of center is a multistory, steel-frame building (0.85 mile from ground zero at Nagasaki).

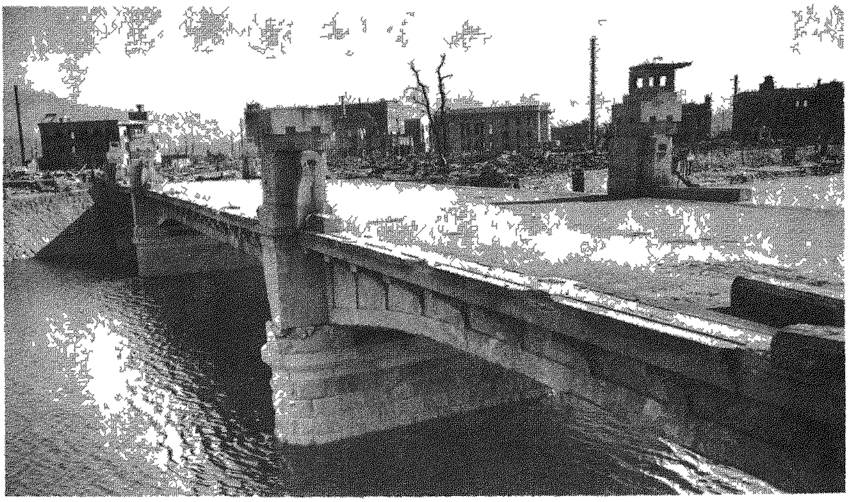

Figure 4.90a. Bridge with deck of reinforced concrete on steel-plate girders: outer girder had concrete facing (270 feet from ground zero at Hiroshima). The railing was blown down but the deck received little damage so that traffic continued

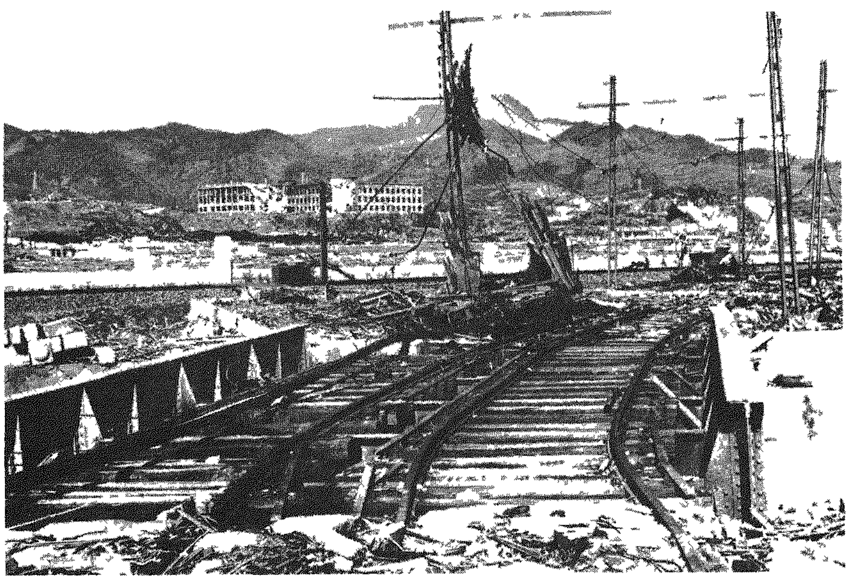

Figure 4.90b. A steel-plate girder, double-track railway bridge (0.16 mile from ground zero at Nagasaki). The plate girders were moved about 3 feet by the blast; the railroad tracks were bent out of shape and trolley cars were demolished, but the poles were left standing.

Figure 4.92a. Effect of nuclear explosion on automobiles in simulated parking lot, Nevada Test Site. Much of the damage to glass, paint, and interiors was due to fires caused by thermal radiation.

Figure 4.92b. Damage to automobile originally located behind wood-frame house (5 psi overpressure) ; the front of this car can be seen in Fig. 4.14. Although badly damaged, the car could still be driven after the explosion.

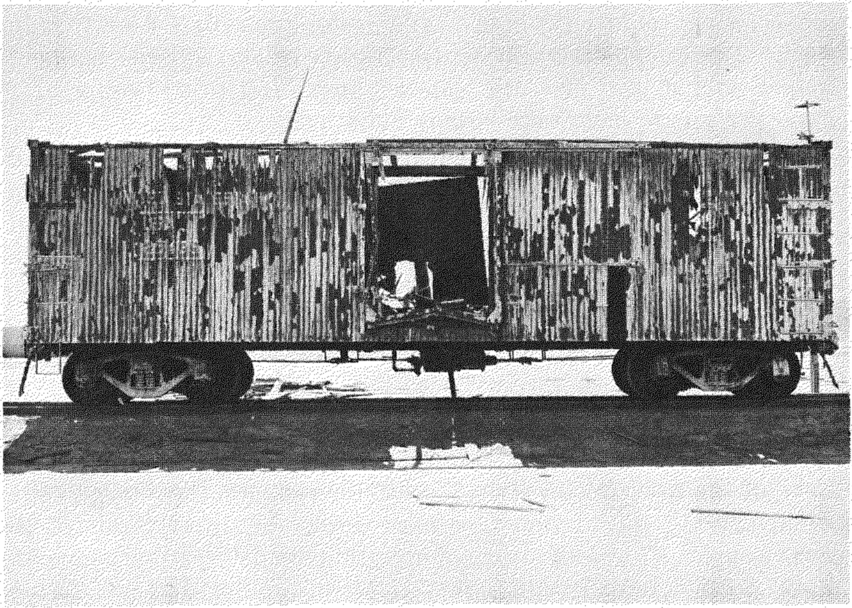

Figure 4.97a. Loaded wooden boxcar after a nuclear explosion (4 psi overpressure).

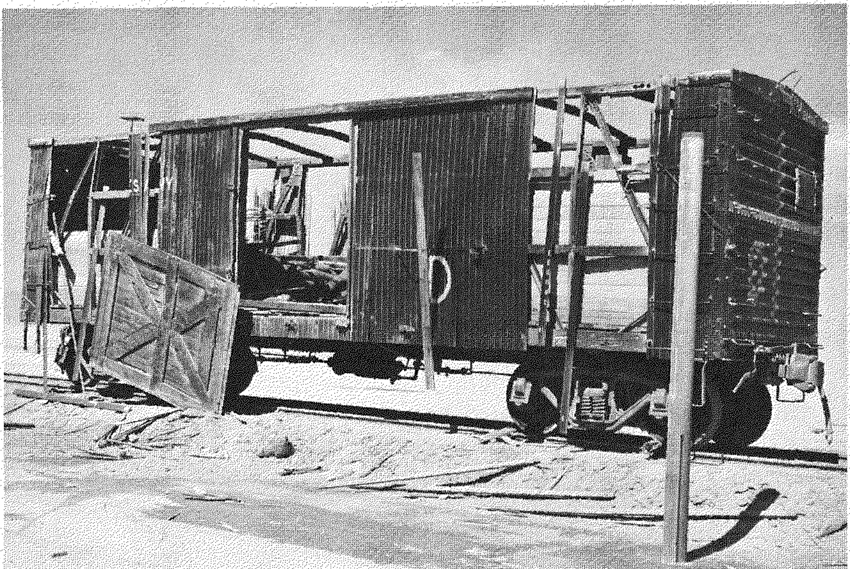

Figure 4.97b. Loaded wooden boxcar after a nuclear explosion (6 psi overpressure).

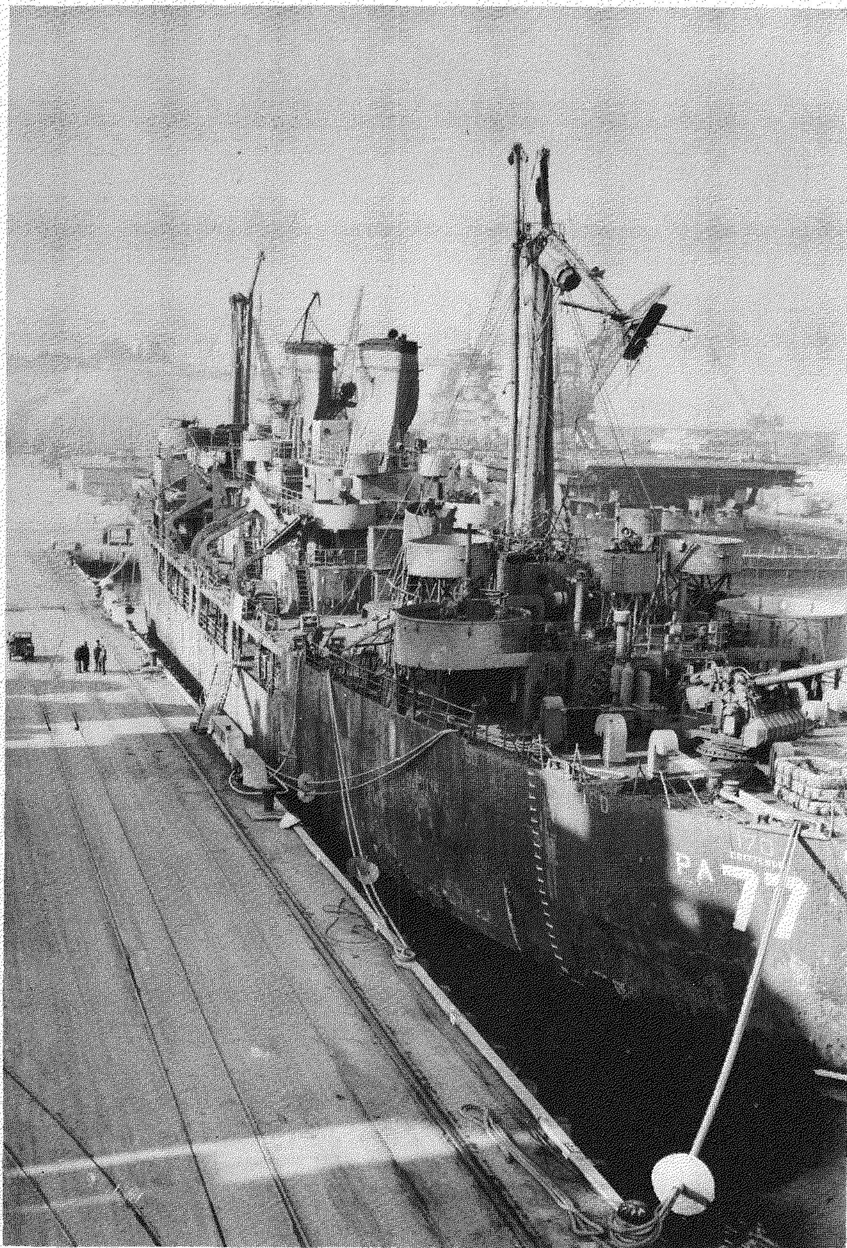

Figure 4.101a. The U. S. S. Crittenden after ABLE test; damage resulting was generally moderate (0.47 mile from surface zero).

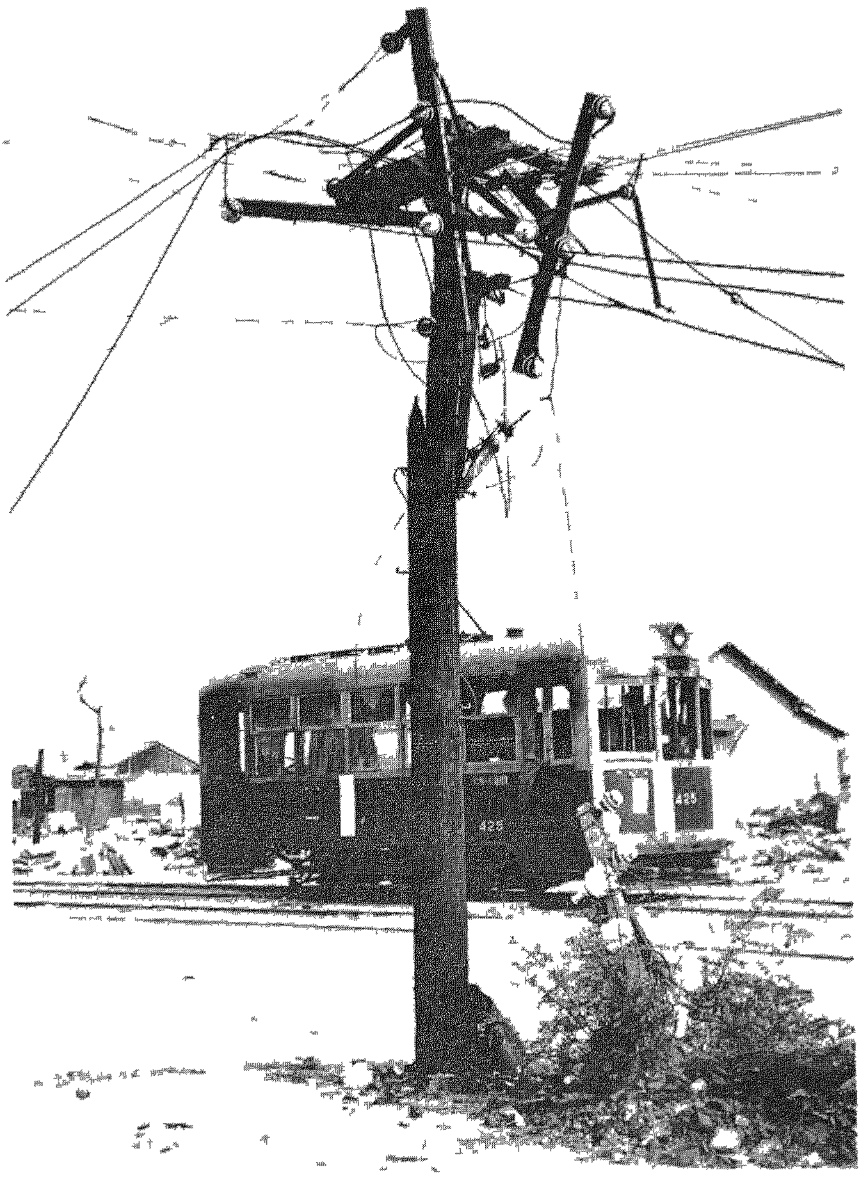

Figure 4 105 Damage to utility pole (0 80 mile from ground zero at Hiroshima)

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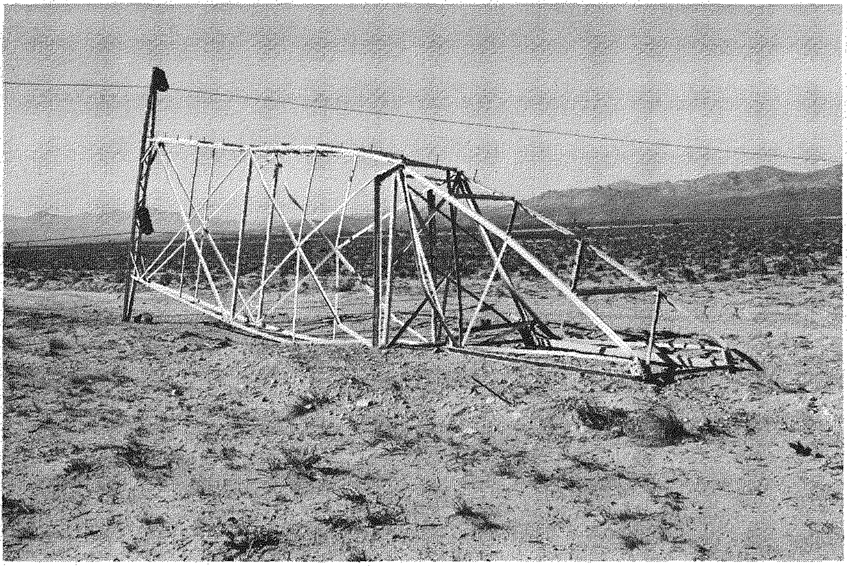

Figure 4.109a. Collapsed suspension tower (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).

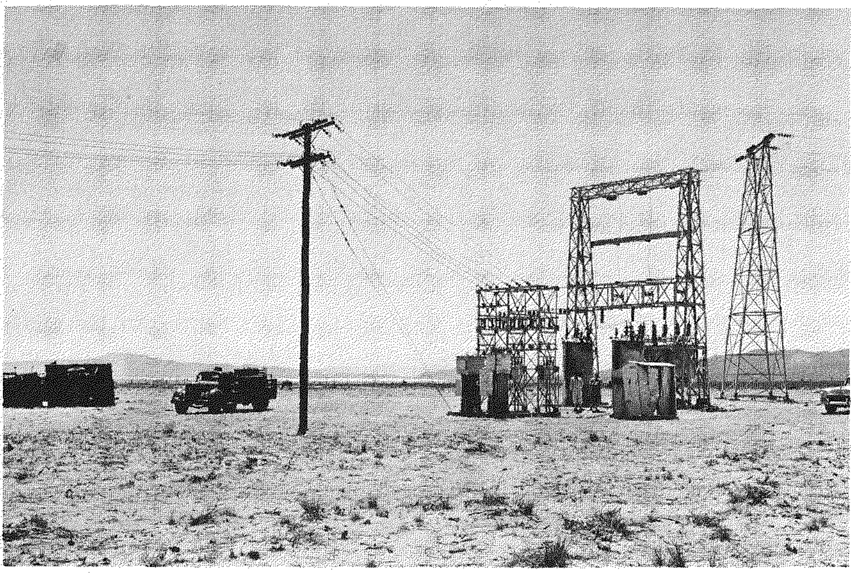

Figure 4.109b. Dead-end tower, suspension tower, and transformers (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).

Table 4.135a Damage Ranges for 20-Kiloton Typical Air Burst

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Miles from Ground Zero	
					Light damage to window frames and doors, moderate plaster damage out to about 4 miles; glass breakage possible out to 8 miles.
40	1.27	–	1.1	2.6	Oil storage tanks, filled : slight damage.
46	1.22	–	1.3	2.4	
53	1.17	–	1.5	2.2	
60	1.11	–	1.7	2.0	Wood frame houses : moderate damage.
70	1.06	0.09	2.0	1.8	Fine kindling fuels : ignited.
					Radio and TV transmitting towers : slight damage. Smokestacks : slight damage.
86	1.00	0.15	2.5	1.6	
					Light steel frame industrial buildings, light walls : moderate damage.
					Wood frame houses : severe damage.
105	0.96	0.23	3.1	1.4	Motor vehicles : slight damage. Radio and TV transmitting towers : moderate damage.
133	0.91	0.39	4.0	1.2	Medium steel frame industrial buildings, light walls : moderate damage. Telephone and power lines : limit of significant damage.
					Wood frame houses : destroyed. Highway and R.R. truss bridges : slight damage. Wall bearing, brick (apartment house type) buildings : moderate damage.
153	0.85	0.70	5.4	1.0	Steel frame, light walls (office type) buildings : moderate damage.
					Reinforced concrete frame and walls, multistory structures : moderate damage. Wall bearing, brick (apartment house type) buildings : severe damage.
234	0.78	1.2	7.6	0.8	Reinforced concrete frame building, light walls : moderate damage. *Highway and R. R. truss bridges : moderate damage.*
					Medium steel frame industrial buildings, light walls : severe damage. Reinforced concrete frame and walls, multistory structures : severe damage.
294	0.71	2.2	10	0.6	Massive wall bearing, multistory structures : moderate damage. Motor vehicles : moderate damage.
					Steel frame, light walls (office type) buildings : severe damage. Oil storage tanks, filled : severe damage.
384	0.64	3.5	14	0.4	
					Motor vehicles : severe damage.
					Reinforced concrete, blast resistant, windowless structures : moderate damage. All other (above ground) structures : severely damaged or destroyed.
306	0.55	2.5	24	0.2	
				0	Ground zero for 20-kiloton air burst.

Table 4.135b Damage Ranges for 1–Megaton Typical Air Burst

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Miles from Ground Zero	Damage
36	4.8	–	1.0	10	Light damage to window frames and doors moderate plaster damage out to about 15 miles glass breakage possible out to 30 miles
					Oil storage tanks filled slight damage
43	4.6	–	1.2	9	
					Fine kindling fuels ignited
53	4.3	–	1.5	8	
					Wood frame houses moderate damage Radio and TV transmitting towers slight damage Smokestacks slight damage
63	4.0	0.08	1.8	7	
83	3.8	0.13	2.4	6	
					Light steel frame industrial buildings, light walls moderate damage Motor vehicles slight damage Radio and TV transmitting towers moderate damage Wood frame houses severe damage
109	3.5	0.26	3.2	5	
					Medium steel frame industrial buildings light walls moderate damage Telephone and power lines limit of significant damage Highway and R R truss bridges slight damage Steel frame, light walls (office type) buildings moderate damage
142	3.2	0.55	4.7	4	Wood frame houses destroyed Wall bearing, brick (apartment house type) buildings moderate damage
					Reinforced concrete frame and walls, multistory structures moderate damage Wall bearing, brick (apartment house type) buildings severe damage Reinforced concrete frame buildings light walls moderate damage
228	2.9	1.2	7.4	3	Highway and R R truss bridges moderate damage Medium steel frame industrial buildings, light walls severe damage
					Reinforced concrete frame and walls, multistory structures severe damage Massive wall bearing multistory structures moderate damage Steel frame, light walls (office type) buildings severe damage Motor vehicles moderate damage
317	2.6	2.6	11	2	Oil storage tanks, filled severe damage
					Motor vehicles severe damage
347	2.1	3.2	20	1	
					Reinforced concrete, blast resistant, windowless structures moderate damage All other (above ground) structures severely damaged or destroyed
				0	Ground zero for 1–megaton air burst

Bikini BAKER test. A more generalized treatment of wave heights, which can be adapted to shallow underwater explosions of any specified energy, is given later in this chapter.

TABLE 5.40

MAXIMUM HEIGHTS (CREST TO TROUGH) AND ARRIVAL TIMES OF WATER WAVES AT BIKINI BAKER TEST

Distance (yards)	330	660	1, 330	2, 000	2, 700	3, 300	4, 000
Wave height (feet)	94	47	24	16	13	11	9
Time (seconds)	11	23	48	74	101	127	154

5.41 It appears probable that the large waves were responsible for some of the ship damage which occurred in the BAKER test. Fairly definite evidence of the destruction caused by water waves to the carrier U. S. S. Saratoga, anchored with its stern 400 yards from surface zero, was obtained from a series of photographs taken at 3-second intervals. A photograph taken before any visible shock effect had reached the Saratoga shows the island structure and the radar mast undamaged. In a photograph taken 9 seconds later, the radar mast is seen to be bent over by the blast wave, but the island structure is yet unaffected. This photograph shows the stern of the vessel rising on the first wave crest, at least 43 feet above its previous position, but shortly thereafter it was obscured from view by the base surge.

5.42 When the Saratoga was again visible, after the major waves and other effects had subsided, the central part of the island structure was observed to be folded down on the deck of the carrier (Fig. 5.42). It appears highly probable that shortly after the rise on the first wave crest, the Saratoga fell into the succeeding trough and was badly hit by the second wave crest, causing the damage to the island structure.

CHANGE IN THE LAGOON BOTTOM

5.43 The explosion of the Bikini BAKER bomb caused a measurable increase in depth of the bottom of the lagoon over an area roughly 2,000 feet across. The greatest apparent change in depth was 32 feet, but this represents the removal of an elevated region rather than an excavation in a previously flat surface. Before the test, samples of sediment collected from the bottom of the lagoon consisted of coarse-grained algal debris mixed with less than 10 percent of sand and mud. Samples taken after the explosion were, however, quite different. Instead of algal debris, layers of mud, up to 10 feet thick, were found

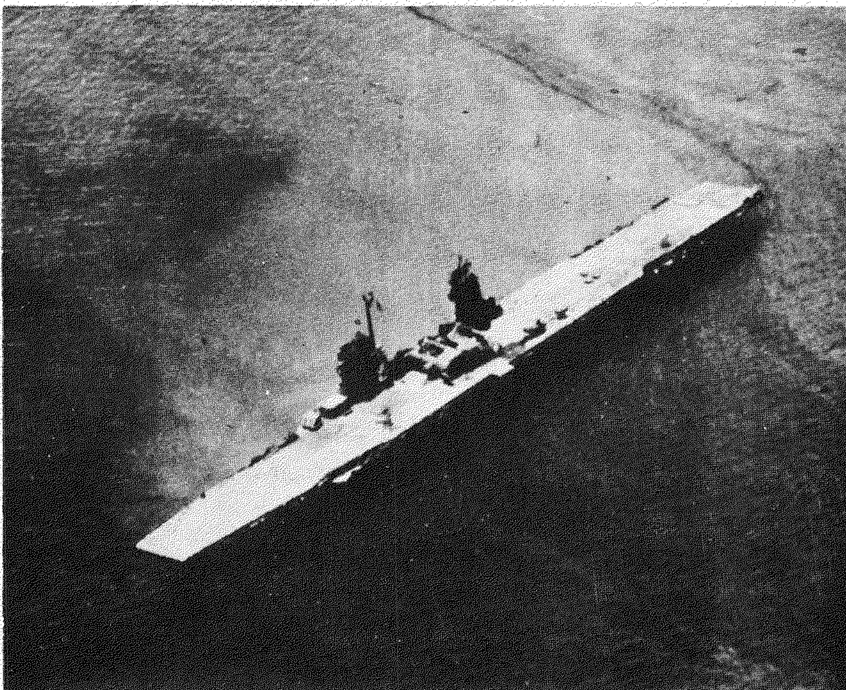

Figure 5.42. The aircraft carrier U. S. S. Saratoga after the BAKER explosion.

on the bottom near the burst point. Further information on cratering in underwater explosions is given at the end of the chapter.

TECHNICAL ASPECTS OF SURFACE AND UNDERGROUND BURSTS[1]

CRATER DIMENSIONS IN SURFACE BURST

5.44 In addition to the rupture and plastic zones, defined earlier, two other features of a crater may be defined; these are the "apparent crater" and the "true crater." The apparent crater, which has a diameter D_a and a depth H_a, as shown in Fig. 5.44, is the surface of the depression or hole left in the ground after the explosion. The true crater, diameter D_t, on the other hand, is the surface extending beyond the apparent crater where a definite shear has occurred. The volume

[1] The remaining sections of this chapter may be omitted without loss of continuity.

of the (apparent) crater assumed to be roughly paraboloid, is given approximately by

$$\text{Volume of crater} = \frac{\pi D_a^2 H_a}{8}.$$

Using the data given in § 5.7, the crater volume for a 1-kiloton burst at at the surface in dry soil is found to be about 150,000 cubic feet, weighing close to 7,500 tons.

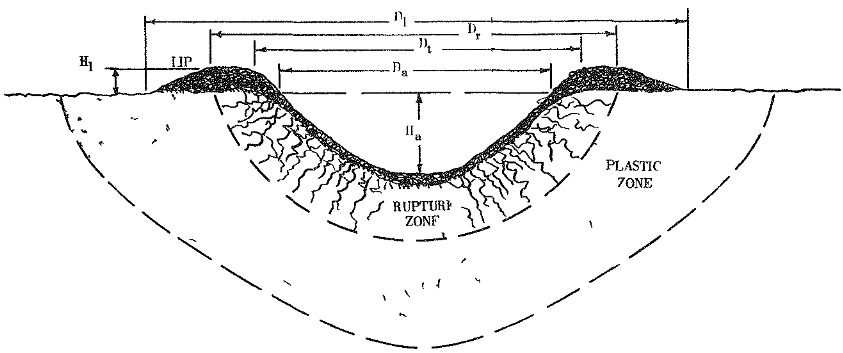

Figure 5.44. Characteristic dimensions of crater in a surface burst.

5.45 The diameter of the rupture zone, indicated by D_r in Fig. 5.44, is roughly one and one-half times the crater diameter, i. e.,

$$D_r \approx 1.5\ D_a.$$

The overall diameter, including the lip, i. e., D_l, is about twice the crater diameter, so that

$$D_l \approx 2\ D_a,$$

and the height of the lip, H_l, is approximately one-fourth of the depth of the crater, i. e.,

$$H_l \approx 0.25\ H_a.$$

5.46 The (apparent) depth and diameter of the crater formed in a surface burst in dry soil of a weapon of energy yield W kilotons, ranging from 1 kiloton to 20,000 kilotons (20 megatons), can be obtained from Fig. 5.46. The plots are based on the scaling laws given in § 5.8, namely, that the crater diameter scales according to $W^{1/3}$ and the depth according to $W^{1/4}$. Various soil characteristics, particularly, the moisture content, affect the dimensions of the crater. Approximate "soil factors" are therefore used to obtain the values in other soils when those in dry soil are known. These factors, together with an example of their application, are given on the page facing Fig. 5.46.

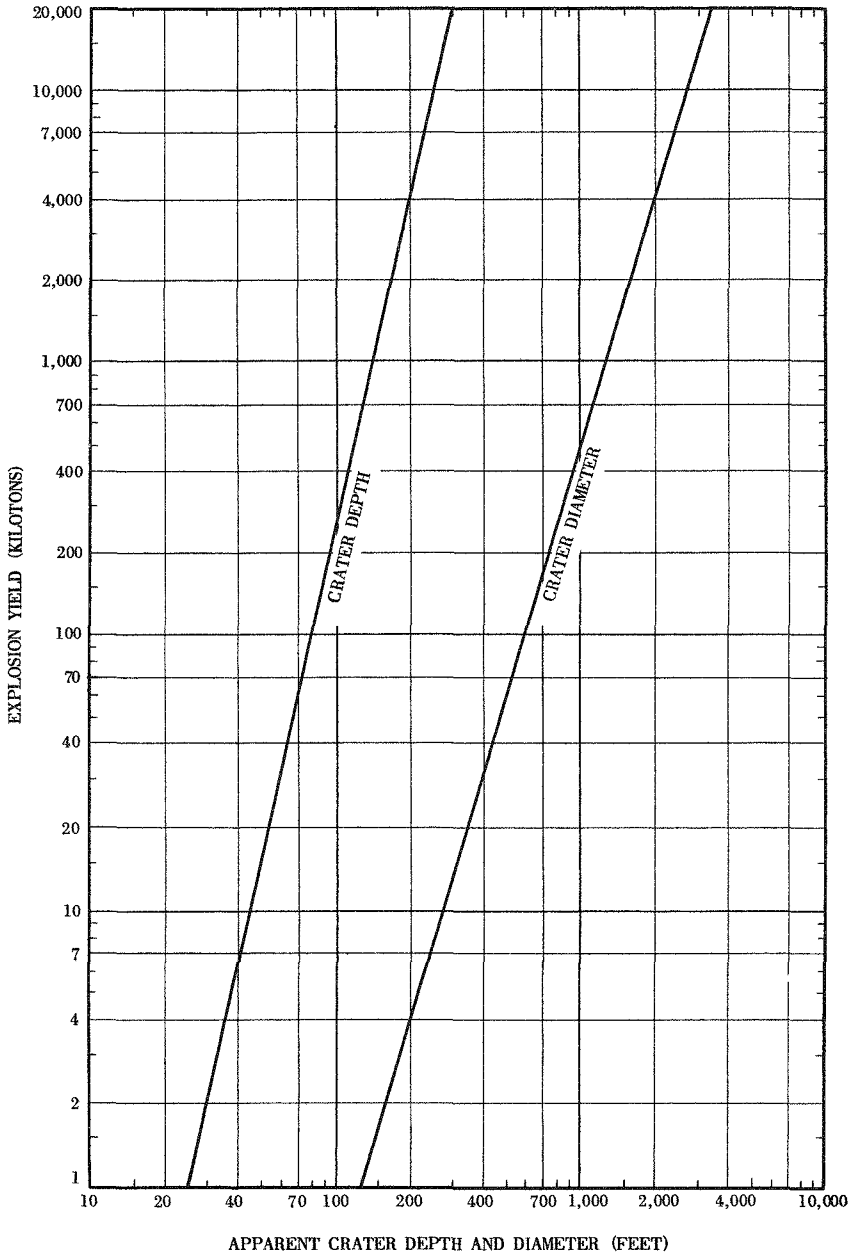

Figure 5.46. Apparent crater depth and diameter for a contact surface burst in dry soil.

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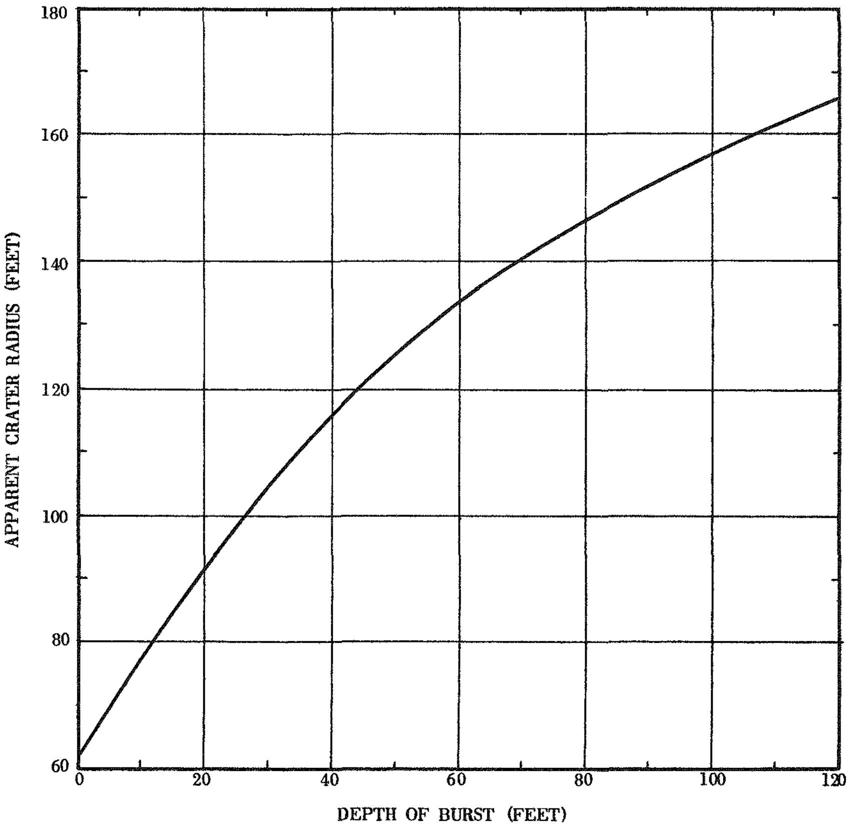

Figure 5.47. Relation of apparent crater radius to depth of burst for 1-kiloton explosion in dry soil.

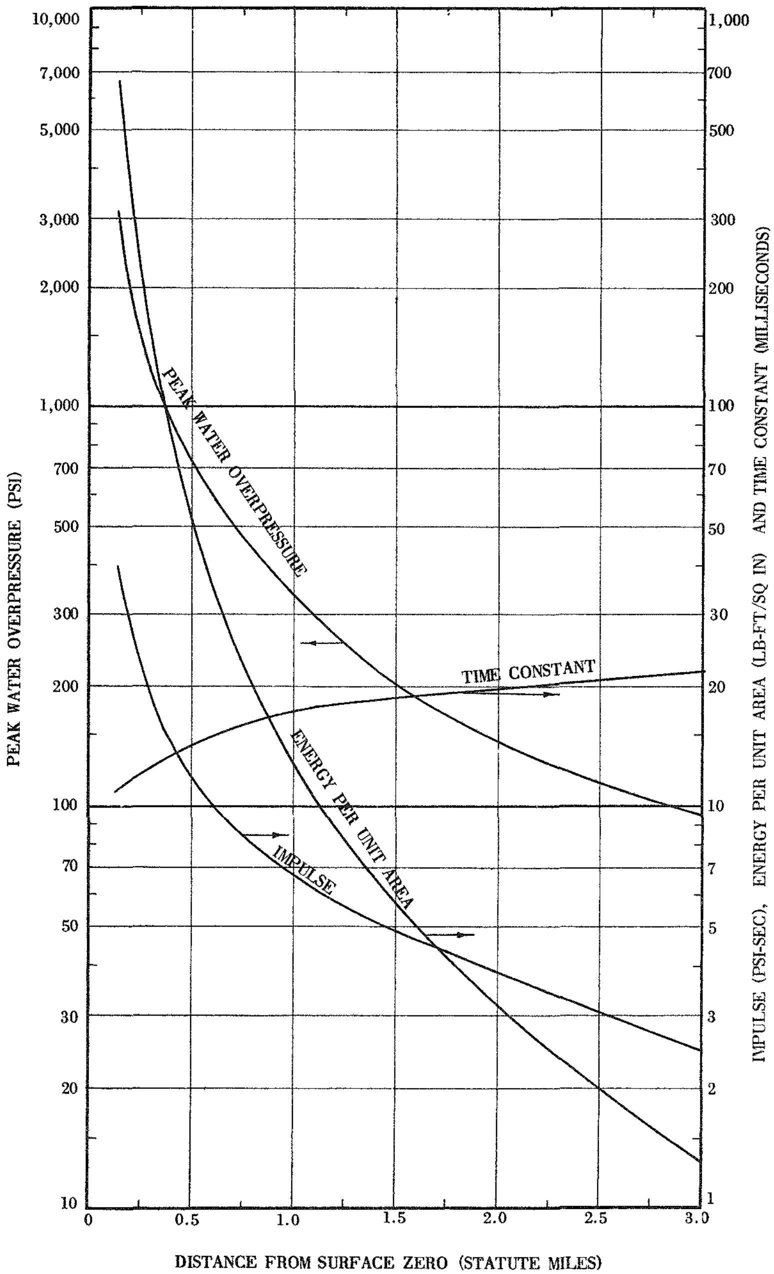

Figure 5.48. Water shock wave properties for a 1-kiloton explosion in deep water.

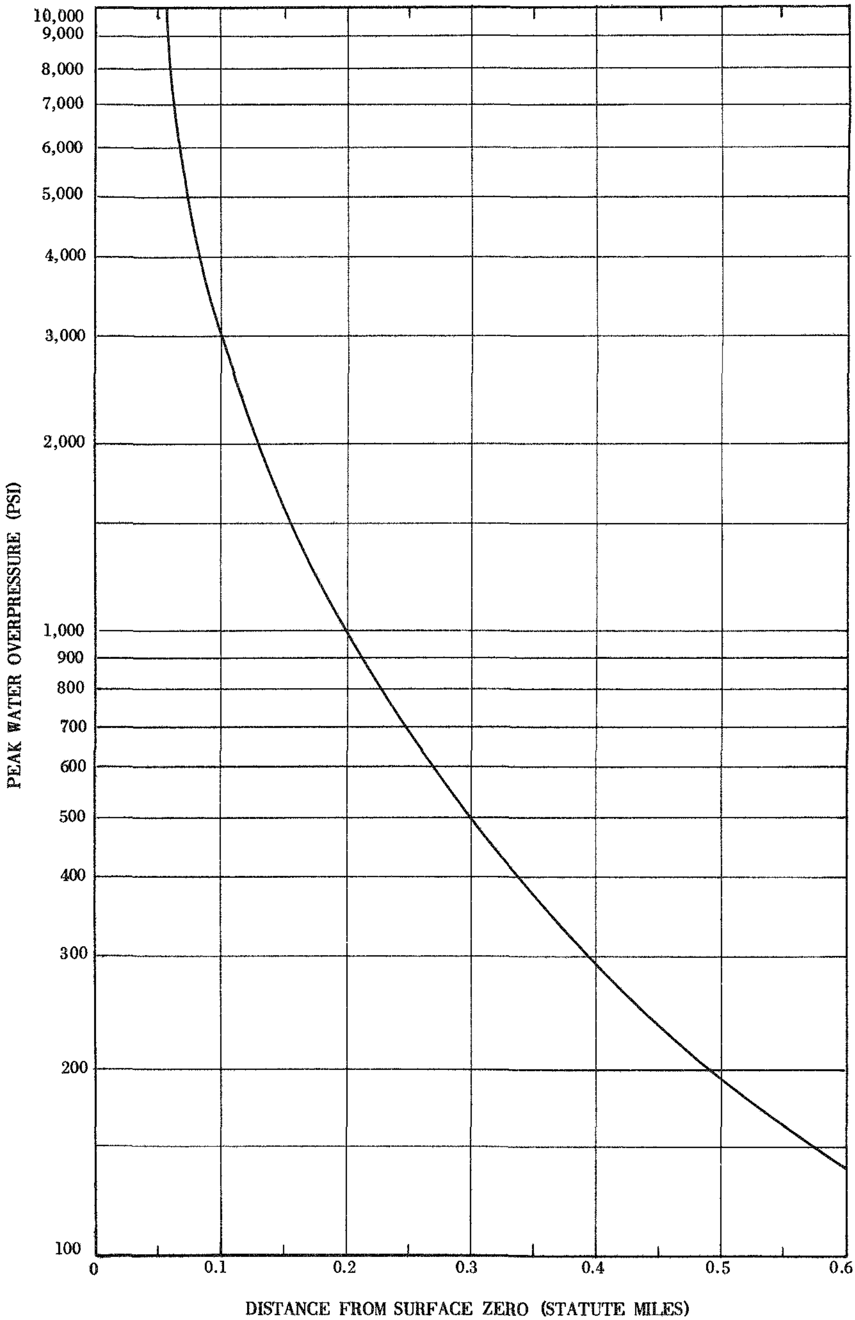

Figure 5.52. Peak water overpressure for a 1-kiloton explosion at mid-depth in water 66 feet deep.

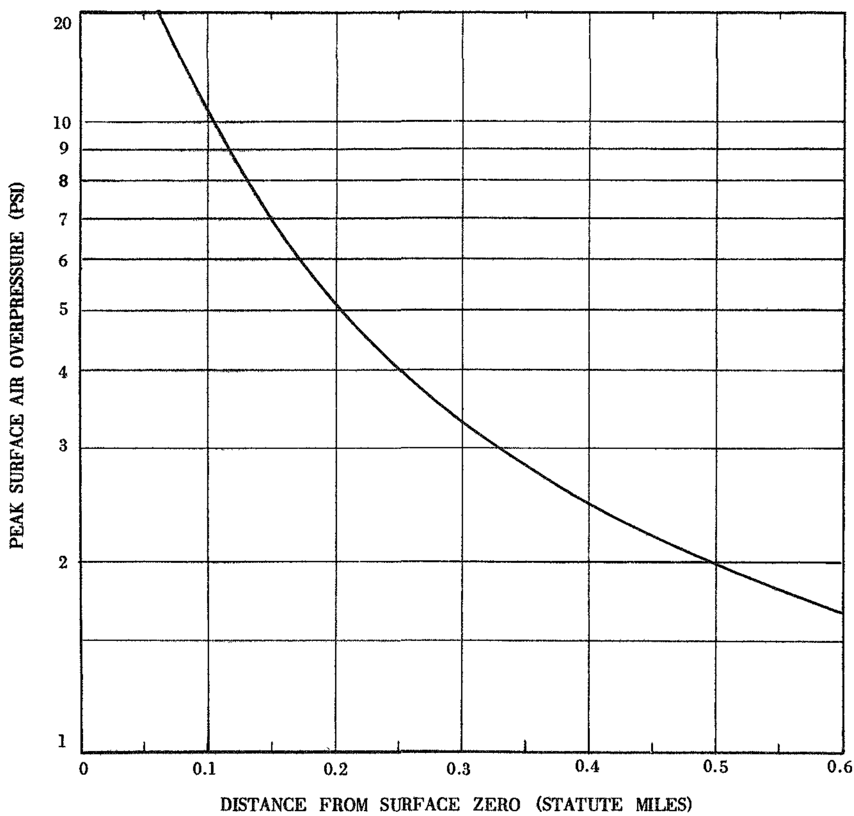

Figure 5.53. Peak air overpressure at surface for a 1-kiloton shallow underwater explosion.

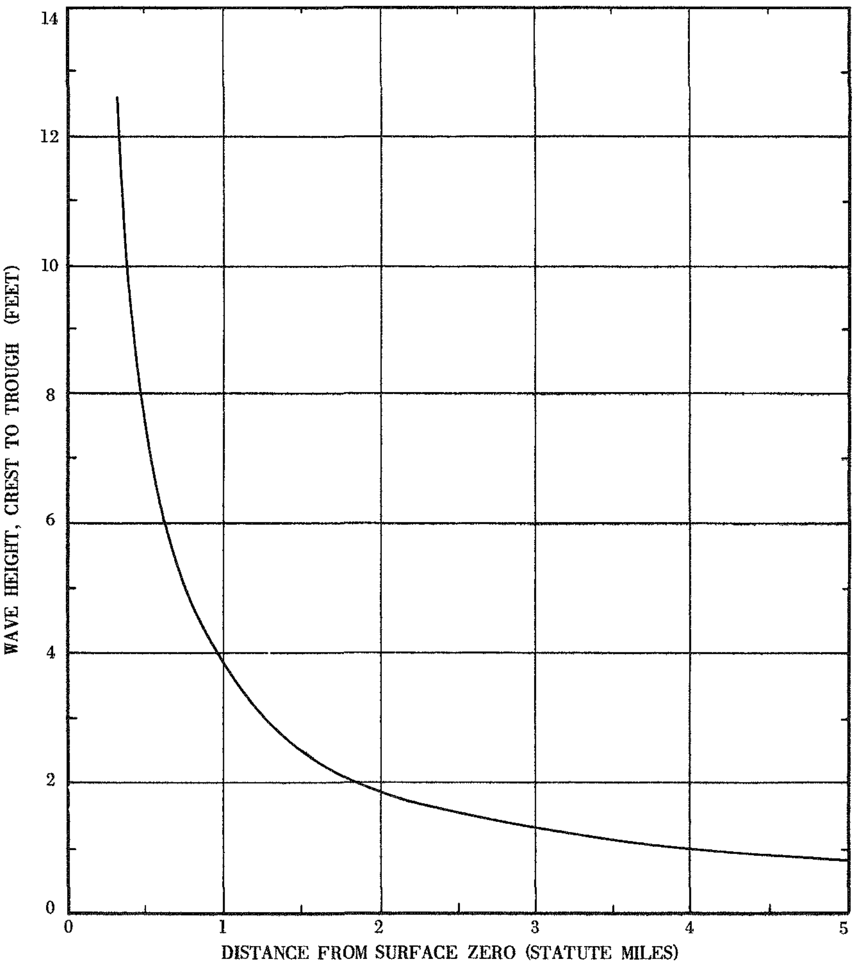

Figure 5.54. Maximum wave height (crest to trough) for a 1-kiloton explosion in water 85 feet deep.

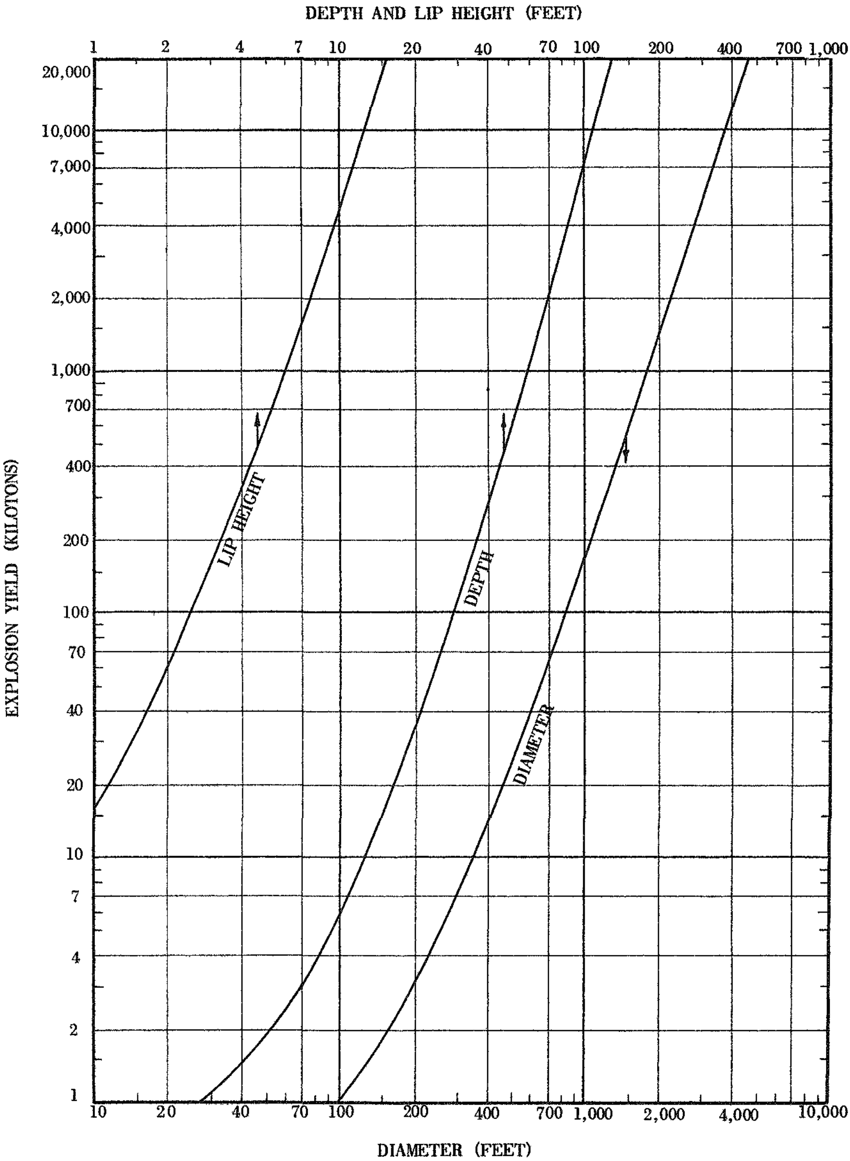

Figure 5.55. Dimensions of crater from underwater burst.

Damage to Above Ground Structures

6.5 The nature of the damage in the B, C, and D classes to various structures are given in Tables 6.5a and b. Since A damage represents virtually complete destruction, it has not been included. For con-

Table 6.5a

STRUCTURAL TYPES PRIMARILY AFFECTED BY BLAST WAVE DURING THE DIFFRACTION PROCESS

Description of structure	Description of damage		
	B	C	D
Multistory reinforced-concrete building,* with reinforced-concrete walls, blast resistant design, no windows, three stories.	Walls shattered, structure frame severely distorted, first floor columns collapse or near collapse.	Walls cracked, building slightly distorted, entranceways damaged, doors blown in or jammed; some spalling of concrete (Fig. 4.82a).	Designed to prevent light damage.
Multistory, reinforced-concrete building, with concrete walls, small window area, five stories.	Walls shattered, severe frame distortion, incipient collapse of first floor columns.	Exterior walls badly cracked, interior partitions badly cracked or blown down, structure frame permanently distorted; spalling of concrete.	Windows and doors blown in, interior partitions cracked.
Multistory, wall-bearing building, brick apartment house type, up to three stories.	Bearing walls collapse resulting in total collapse of structure (Fig. 4.89a).	Exterior walls badly cracked, interior partitions badly cracked or blown down.	Windows and doors blown in, interior partitions cracked.
Multistory, wall-bearing building, massive type, four stories. Large structure (over 200 ft x 200 ft plan dimensions). In this case the side facing the blast may be severely damaged while the interior remains relatively undamaged.	Bearing walls collapse resulting in collapse of structure supported by these walls. Some bearing walls may be shielded enough by intervening walls so that part of structure may receive only moderate damage (Fig. 4.89b).	Exterior walls facing blast badly cracked, interior partitions badly cracked, although toward far end of building damage may be reduced.	Windows and doors blown in, interior partitions cracked.
Wood-frame building, house type, one or two stories.	Frame shattered so that structure is for the most part collapsed (Fig. 4.14).	Wall framing cracked, roof badly damaged, interior partitions blown down (Fig. 4.8).	Windows and doors blown in, interior partitions cracked (Fig. 4.16).
Oil tanks, 30,000 to 100,000 bbl, cone roof; tanks considered full (more vulnerable if empty). Floating roof tanks are less vulnerable.	Large distortions of sides, seams split, so that most of contents are lost (Fig. 4.74a).	Roof collapsed, sides above liquid buckled, some distortion below liquid level.	Roof badly damaged (Fig. 4.74b).

*Designed to withstand 20 psi overpressure in the Mach region from a 20-kiloton weapon without any impairment of facilities.

venience, the structures in the first table are those damaged by forces acting primarily during the diffraction process; these forces are closely related to the reflected overpressure. The second table is concerned with buildings which are affected mainly by drag (dynamic pressure) forces. It will be noted that there is no mention in the tables of high

TABLE 6.5b

STRUCTURAL TYPES PRIMARILY AFFECTED BY DRAG LOADING

Description of structure	Description of damage		
	B	C	D
Light steel-frame industrial building, single story with up to 5 ton crane capacity. Light weight, low strength walls fail quickly.	Severe frame distortion (half column height deflection), (Fig. 4.55a and b).	Some distortion of frame; cranes (if any) cannot operate until repairs made (Fig. 4.62b).	Windows and doors blown in, light siding ripped off or buckled.
Medium steel-frame industrial building, single story with a 20-ton capacity crane. Light weight, low strength walls fail quickly.	Severe frame distortion (half column height deflection).	Some distortion of frame; cranes (if any) cannot operate until repairs made.	Windows and doors blown in, light siding ripped off or buckled.
Heavy steel-frame industrial building, single story with 50 ton crane capacity. Light weight, low strength walls fail quickly.	Severe frame distortion (half column height deflection).	Some distortion of frame; cranes (if any) cannot operate until repairs made.	Windows and doors blown in, light siding ripped off or buckled.
Multistory, steel-frame office type building, five stories. Light weight, low strength walls fail quickly.	Severe frame distortion. Incipient collapse of lower floor columns.	Frame distorted moderately. Interior partitions blown down.	Windows and doors blown in, light siding ripped off, interior partitions cracked or buckled.
Multistory, reinforced-concrete frame office-type building, five stories. Light weight, low strength walls fail quickly.	Severe frame distortion. Incipient collapse of lower floor columns (Fig. 4.82b).	Frame distorted moderately. Interior partitions blown down; some spalling of concrete (Fig. 4.85b).	Windows and doors blown in, light siding ripped off, interior partitions cracked or buckled.
Highway and railroad truss bridges.	Total failure of lateral bracing, collapse of bridge.	Some failure of lateral bracing such that bridge capacity is reduced about 50 percent.	Capacity of bridge unchanged. Barely noticeable distortion of lateral bracing.

buildings, such as are common in many large cities in the United States. This is because information concerning such buildings is lacking. There were no structures of this type in Hiroshima and Nagasaki, and there have been none exposed at the nuclear test explosions.

6.6 For certain structural elements, with short periods of vibration (up to about 0.05 second) and small plastic deformation at failure, the conditions for failure can be expressed as a peak overpressure

without consideration for the duration of the blast wave. The failure conditions for elements of this type are given in Table 6.6. Some of these elements fail in a brittle fashion, and thus there is only a small difference between the pressures that cause no damage and those that produce complete failure. Other elements may fail in a moderately ductile manner, but still with little difference between the pressures for light damage and complete failure. The pressures are incident blast overpressures for panels that face ground zero. For panels that are oriented so that there are no reflected pressures thereon, the incident pressures must be doubled.

TABLE 6.6

CONDITIONS OF FAILURE OF PEAK OVERPRESSURE-SENSITIVE ELEMENTS

Structural Element	Failure	Approximate Incident Blast Overpressure (psi)
Glass windows, large and small.	Shattering usually, occasional frame failure.	0. 5–1. 0
Corrugated asbestos siding.	Shattering.	1. 0–2. 0
Corrugated steel or aluminum paneling.	Connection failure followed by buckling.	1. 0–2. 0
Brick wall panel, 8″ or 12″ thick (not reinforced).	Shearing and flexure failures.	7. 0–8. 0
Wood siding panels, standard house construction.	Usually failure occurs at the main connections allowing a whole panel to be blown in.	1. 0–2. 0
Concrete or cinder-block wall panels, 8″ or 12″ thick (not reinforced).	Shattering of the wall.	2. 0–3. 0

DAMAGE TO LIGHT-WEIGHT EARTH COVERED AND BURIED STRUCTURES

6.7 Air blast is the controlling factor for damage to light-weight earth covered structures and shallow buried underground structures. The earth cover provides surface structures with substantial protection against air blast and also some protection against missiles. The depth of earth cover above the structure would usually be determined by the degree of protection from nuclear radiation required at the design overpressure or dynamic pressure (see Chapter VIII).

TABLE 6 23

DAMAGE CRITERIA FOR TRANSMITTING TOWERS

Damage class	Nature of damage
A and B	Towers demolished or flat on the ground (Fig 4 109a).
C	Towers partially buckled, but held by guy lines, ineffective for transmission.
D	Guy lines somewhat slack, but tower able to transmit (Fig 4.109b).

DAMAGE TO FORESTS

6.24 In considering damage to forests, the discussion will refer more specifically to naturally occurring broadleaf and coniferous stands averaging about 175 trees per acre. Because trees are primarily sensitive to drag forces, the zone in which the damage decreases from class A to class D is relatively narrow. In particular, the transition from A to B is difficult to delineate, and so these two types of damage are taken together. The different classifications are described in Table 6.24. Since the effect of air blast on forests is similar to that of strong

Figure 6.24a. Forest stand after a nuclear explosion, B damage (3.8 psi overpressure).

Figure 6.24b. Forest stand after a nuclear explosion, C damage (2.4 psi overpressure).

TABLE 6.24

DAMAGE CRITERIA FOR FORESTS

Damage class	Nature of damage	Equivalent hurricane wind velocity (miles per hour)
A & B	Up to 90 percent of trees blown down; remainder denuded of branches and leaves (Fig. 6.24a). (Area impassable to vehicles and very difficult on foot.)	130–140
C	About 30 percent of trees blown down; remainder have some branches and leaves blown off (Fig. 6 24b). (Area passable to vehicles only after extensive clearing.)	90–100
D	Very few trees blown down, some leaves and branches blown off. (Area passable to vehicles.)	60–80

winds, the velocities of steady winds which would produce comparable damage are included in the table.

6.25 The damage-distance relationship for average forest stands are given in Fig. 6.41c. The distances for broadleaf stands are somewhat greater than the average, whereas those for coniferous stands are slightly less.

DAMAGE FROM GROUND AND WATER SHOCK

Underground Structures

6.26 An underground structure can be designed so as to be practically immune to air blast (§6.14), but such structures can be damaged or destroyed by cratering or by ground shock due to a near surface, true surface, or underground burst. The average density of an underground structure will usually be less than that of the displaced soil. In addition, it is known that the pressure pulse in the soil from a contact surface burst or an underground burst is relatively long compared to the dimensions of the structure, and the pressure at the shock front does not increase abruptly.

6.27 On the basis of these facts, it is to be expected that underground structures of relatively small size will "roll with the blow." This expectation has been borne out by actual experience. The movement of the structure is intimately connected with the movement of the soil as the shock wave passes. In other words, if the particle acceleration in the soil has certain peak horizontal and vertical components, then the small underground structure may be expected to have almost the same peak acceleration components.

6.28 As stated in § 5.18, *et seq.*, the criteria for damage caused by cratering and ground shock may be described in terms of three regions, namely (1) the crater itself; (2) the region extending roughly out to the limit of the plastic zone, i. e., to approximately two and one-half times the crater radius; and (3) the zone in which transient earth movements occur without permanent measurable deformation, there being no appreciable ground shock damage in this region.

6.29 The shock parameter mainly responsible for damage has not been defined either theoretically or empirically. However, there is considerable evidence that the degrees of damage can be related, without serious error, to the crater radius. Some examples of this type of relationship are given in Table 6.29. There are certain minor variations in the distances due to the factors referred to in § 5.18, as well as

to the characteristics of the soil or rock in which the structure is buried. It will be seen that, as is to be anticipated, there is no appreciable damage from ground shock beyond the plastic zone, i. e., farther than about two and one-half crater radii from surface zero.

TABLE 6.29

GROUND SHOCK DAMAGE CRITERIA FOR MODERATELY DEEP UNDERGROUND STRUCTURES

Type of structure	Damage class	Distance from surface zero	Nature of damage
Relatively small, heavy, blast-resistant design (shelters).	A & B	1¼ crater radii.	Collapse or severe displacement.
	C	1¼ to 2 crater radii.	Shock damage to interior equipment.
	D	2 to 2½ crater radii.	Severance of brittle connections, slight cracking at structural discontinuities.
Relatively long, flexible (pipelines).	A	1½ crater radii.	Deformation and rupture.
	B	1½ to 2 crater radii.	Slight deformation with some rupture.
	C	2 to 3 crater radii.	Failure of connections.

6.30 A heavy, reinforced-concrete underground shelter is an example of the first type of structure referred to in Table 6.29. This may be expected to survive just beyond the crater region. But, attention should be called to the fact that the structure would be covered with the highly radioactive earth (see § 9.58) of the crater lip out to the limit of class C damage.

6.31 Buried utility pipes would be representative of the long, flexible structure in Table 6.29. The damage in zones A and B is primarily a result of permanent displacement of the soil, and in zone C it is due to permanent or transient strains. The actual distance to which type C damage will extend is dependent upon the orientation of the pipeline with respect to the explosion center. It is expected that a radial orientation will result in greater damage than a transverse orientation at a given range. Failure is most likely to occur at structural discontinuities, such as at lateral connections and entrances to buildings. This will particularly be the case if brittle materials are involved.

TABLE 6.63

BLAST WAVE CHARACTERISTICS FOR DETERMINATION OF LOADING

Property	Symbol	Source
Peak overpressure	p	Fig. 3.94a and b
Time variation of overpressure	$p(t)$	Fig. 3.82
Peak dynamic pressure	q	Fig. 3.95
Time variation of dynamic pressure	$q(t)$	Fig. 3.82
Reflected pressure at normal incidence	p_r	Fig. 3.80 or equation (3.81.1)
Duration of positive phase	t_+	Fig. 3.96
Blast front (shock) velocity	U	Fig. 3.80

simplify the treatment, it will be supposed, as above, that one side of the structure faces toward the explosion and is perpendicular to the direction of propagation of the blast wave. This side is called the front face. The loading diagrams are computed below for (*a*) the front face, (*b*) the side and top, and (*c*) the back face. By combining the data for (*a*) and (*c*), the net horizontal loading is obtained in (*d*).

6.65 (*a*) *Average Loading on Front Face.*—The first step is to determine the reflected pressure, p_r; this gives the pressure at the time $t=0$, when the blast wave front strikes the front face (see Fig. 6.65). Next, the time t_s, is calculated at which the stagnation pressure, p_s, is first attained. It has been found, from laboratory studies, that t_s can be represented, to a good approximation, by

$$t_s=\frac{3S}{U},$$

where S is equal to H or to $\frac{1}{2}B$, whichever is less. The drag coefficient for the front face is unity, so that the drag pressure is here equal to the dynamic pressure. The stagnation pressure is thus

$$p_s=p(t_s)+q(t_s),$$

where $p(t_s)$ and $q(t_s)$ are the overpressure and dynamic pressure at the time t_s. The pressure subsequently decays with time, so that,

$$\text{Pressure at time } t=p(t)+q(t),$$

where t is any time between t_s and t_+. The pressure-time curve for the front face can thus be determined, as in Fig. 6.65.

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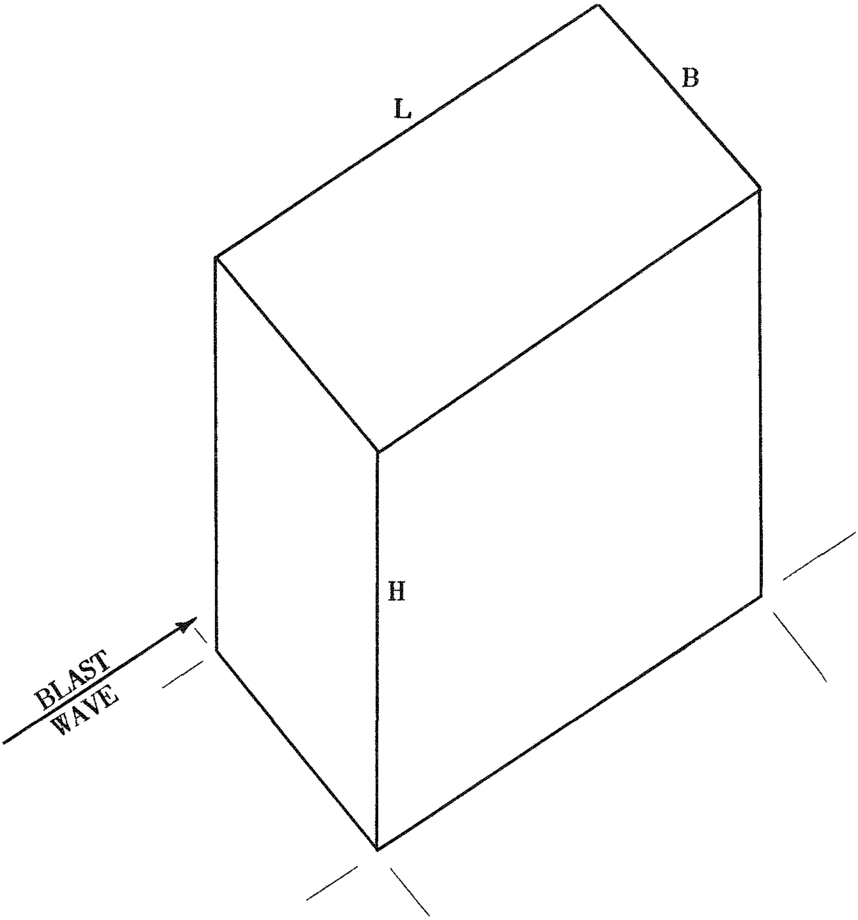

Figure 6.64. Representation of closed box-like structure.

6.66 (*b*) *Average Loading on Sides and Top.*—Although loading commences immediately after the blast wave strikes the front face, i. e., at $t=0$, the sides and top are not fully loaded until the wave has traveled the distance L, i. e., at time $t=L/U$. The average pressure, p_a, at this time is considered to be the overpressure plus the drag loading at the distance $L/2$ from the front of the structure, so that,

$$p_a=p\left(\frac{L}{2U}\right)-\frac{q}{2}\left(\frac{L}{2U}\right),$$

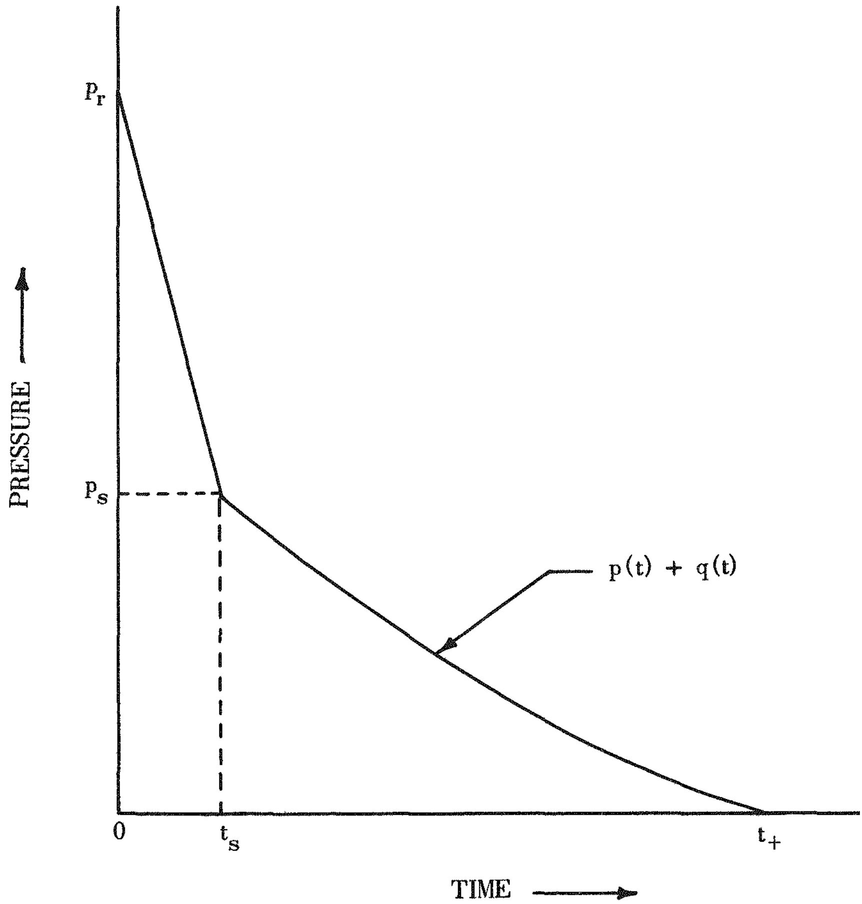

Figure 6.65. Average front face loading of closed box-like structure.

the drag coefficient on the sides and top of the structure being $-\frac{1}{2}$. The loading thus increases from zero at $t=0$ to the value p_a at the time L/U, as shown in Fig. 6.66. After this time the pressure at any time t is given by

$$\text{Pressure at time } t = p\left(t - \frac{L}{2U}\right) - \frac{q}{2}\left(t - \frac{L}{2U}\right),$$

where t lies between L/U and $t_+ + L/2U$, as shown in Fig. 6.66. The overpressure and dynamic pressure, respectively, are the values at the time $t - L/2U$.

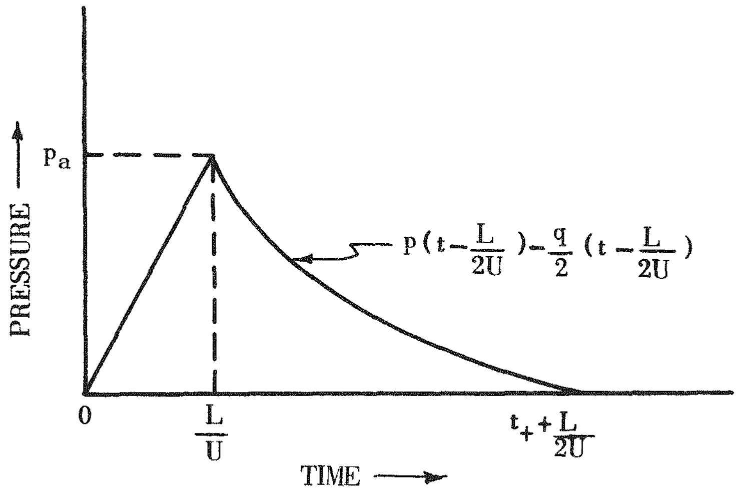

Figure 6.66. Average side and top loading of closed box-like structure.

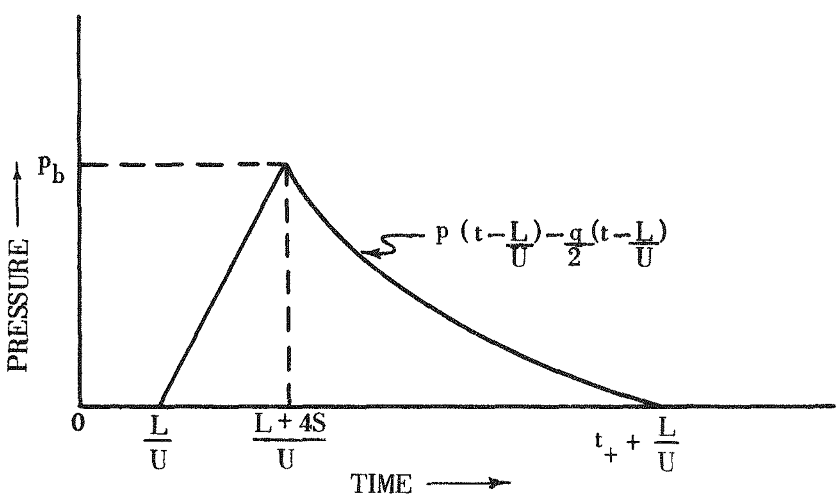

Figure 6.67. Average back face loading of closed box-like structure.

6.67 (*c*) *Average Loading on Back Face.*—The shock front arrives at the back face at time L/U, but it requires an additional time, $4S/U$, for the pressure to build up to the value p_b (Fig. 6.67). Here, as before, S is equal to H or $\frac{1}{2}B$, whichever is the smaller. The drag

coefficient on the back face is $-\frac{1}{2}$, and so the pressure at any time after p_b is attained is represented by

$$\text{Pressure at time } t = p\left(t - \frac{L}{U}\right) - \frac{q}{2}\left(t - \frac{L}{U}\right),$$

where t lies between $(L+4S)/U$ and $t_{+}+L/U$, as seen in Fig. 6.67.

6.68 (*d*) *Net Horizontal Loading.*—The net loading is equal to the front loading minus the back loading. This subtraction is best performed graphically, as shown in Fig. 6.68. The left-hand diagram gives the individual front and back loading curves, as derived from

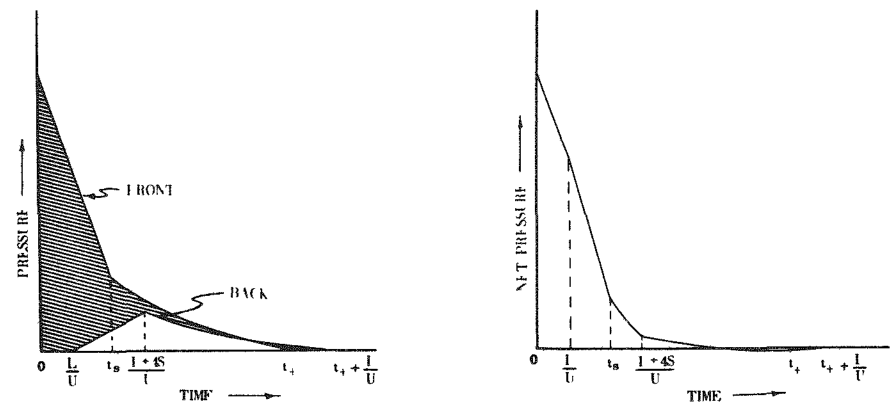

Figure 6.68. Net horizontal loading of closed box-like structure.

Figs. 6.65 and 6.67, respectively. The difference indicated by the shaded region is then transferred to the right-hand diagram to give the net pressure. The net loading is necessary for determining the frame response, whereas the wall actions are governed primarily by the loadings on the individual faces.

Partially Open Box-Like Structure

6.69 Such a structure is one in which the front and back walls have about 30 percent of openings or window area. As in the previous case, the loading is derived for (*a*) the front face, (*b*) the sides and roof, (*c*) the back face, and (*d*) the net horizontal loading. Because the blast wave can now enter the inside of the structure, the loading-time curves must be considered for both the exterior and interior of the structure.

6.70 (*a*) *Average Loading on Front Face.*—The outside loading is computed in the same manner as that used for a closed structure, except that S is replaced by S'. The quantity S' is the average distance (for the entire front face) from the center of a wall section to an open edge of the wall. It represents the average distance which rarefaction waves must travel on the front face to reduce the reflected pressures to the stagnation pressure.

6.71 The pressure on the inside of the front face starts rising at zero time, because the blast wave immediately enters through the openings, but it takes a time $2L/U$ to reach the blast wave overpressure value. Subsequently, the inside pressure at any time t is given by $p(t)$. The dynamic pressures are assumed to be negligible on the interior of the structure. The variations of the inside and the outside pressures with time are as represented in Fig. 6.71.

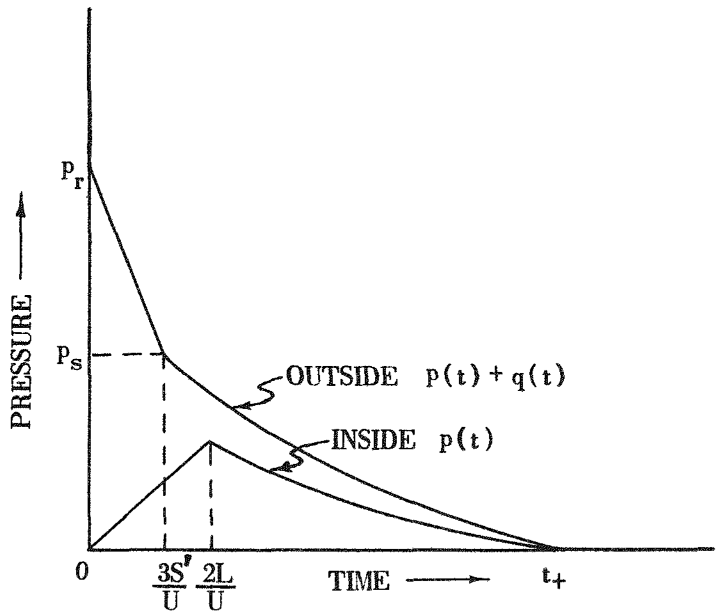

Figure 6.71. Average front face loading of partially open box-like structure.

6.72 (*b*) *Average Loading on Sides and Top.*—The outside pressures are obtained as for a closed structure, but the inside pressures, as for the front face, require a time $2L/U$ to attain the overpressure in the blast wave. Here also, the dynamic pressures on the interior

are neglected, and side wall openings are ignored because their effect on the loading is uncertain. The loading curves are depicted in Fig. 6.72.

6.73 (*c*) *Average Loading on Back Face.*—The outside pressures are the same as for a closed structure, with the exception that S is re-

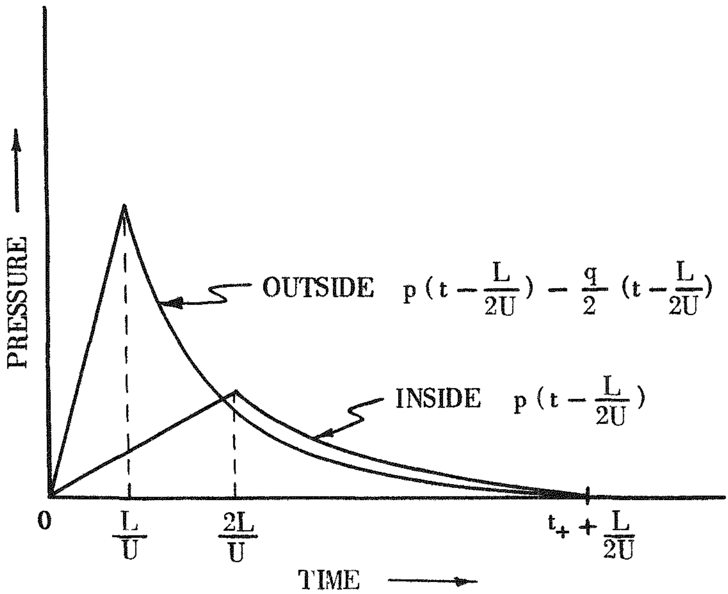

Figure 6.72. Average side and top loading of partially open box-like structure.

placed by S', as described above. The inside pressure, reflected from the inside of the back face, reaches the same value as the blast overpressure at a time L/U and then decays as $p(t-L/U)$; as before, the dynamic pressure is regarded as being negligible (Fig. 6.73). These results are based on the assumption that there are no partitions to influence the passage of the blast wave through the structure.

6.74 (*d*) *Net Horizontal Loading.*—The net horizontal loading is equal to the net front loading, i. e., outside minus inside, minus the net back face loading.

Open Frame Structure

6.75 A structure in which small separate elements are exposed to a blast wave, e. g., a truss bridge, may be regarded as an open frame

structure. Steel-frame office buildings, with a majority of the wall area of glass, or industrial buildings, with asbestos, light steel, or aluminum panels, quickly become open frame structures after the initial impact of the blast wave.

6.76 It is difficult to determine the magnitude of the loading that

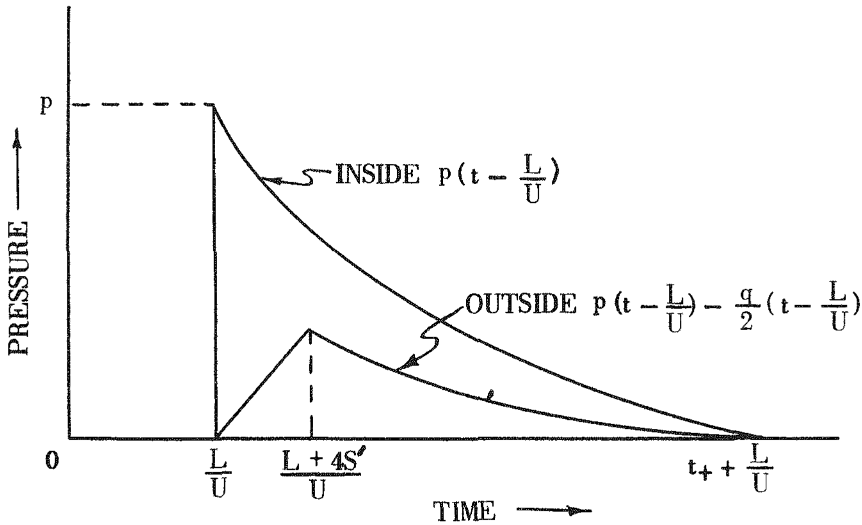

Figure 6.73. Average back face loading of partially open box-like structure.

the frangible wall material transmits to the frame before failing. For glass, the load transmitted is assumed to be negligible if the loading is sufficient to fracture the glass. For asbestos, transite, corrugated steel, or aluminum paneling, an approximate value of the load transmitted to the frame is an impulse of 0.04 pound-second per square inch. Depending on the span lengths and panel strength, the panels are not likely to fail when the peak overpressure is less than about 2 pounds per square inch. In this event, the full blast load is transmitted to the frame.

6.77 Another difficulty in the treatment of open frame structures arises in the computation of the overpressure loading on each individual member during the diffraction process. Because this process occurs at different times for various members and is affected by shielding of one member by adjacent members, the problem must be simplified. A recommended simplification is to treat the loading as an impulse, the value of which is obtained in the following manner. The

overpressure loading impulse is determined for an average member treated as a closed structure and this is multiplied by the number of members. The resulting impulse is considered as being delivered at the time the shock front first strikes the structure, or it can be separated into two impulses for front and back walls where the majority of the elements are located and applied, as shown below in Fig. 6.79.

6.78 The major portion of the loading on an open frame structure consists of the drag (dynamic pressure) loading. For an individual member in the open, the drag coefficient for I-beams, channels, angles, and for members with rectangular cross section is approximately 2.0. However, because in a frame the various members shield one another to some extent from the full blast loading, the average drag coefficient when the whole frame is considered is reduced to 1.0. The force F, i. e., pressure multiplied by area, on an individual member is thus given by

$$F \text{ (member)} = C_d q(t) A_i,$$

where C_d is 2.0 and A_i is the member area projected perpendicular to the direction of blast propagation. For the loading on the frame, however, the force is

$$F \text{ (frame)} = C_d q(t) \Sigma A_i,$$

where C_d is 1.0 and ΣA_i is the sum of the projected areas of all the members. The result may thus be written in the form,

$$F \text{ (frame)} = q(t) A,$$

where $A = \Sigma A_i$.

6.79 The loading (force) versus time for a frame of length L, having major areas in the planes of the front and rear walls, is shown in Fig. 6.79. The symbols A_{fw} and A_{bw} represent the areas of the front and back walls, respectively, which transmit loads before failure, and I_{fm} and I_{bm} are the overpressure loading impulses on front and back members, respectively. It is seen that the drag force does not attain its full value of $q(L/2U)$ until the time L/U, i. e., when the blast wave reaches the end of the structure.

Cylindrical Structure

6.80 The following treatment, which is limited to peak overpressures of less than 30 pounds per square inch, is applicable to structures having a circular cross section, such as telephone poles and smokestacks. It can also be applied to structures with semicircular cross

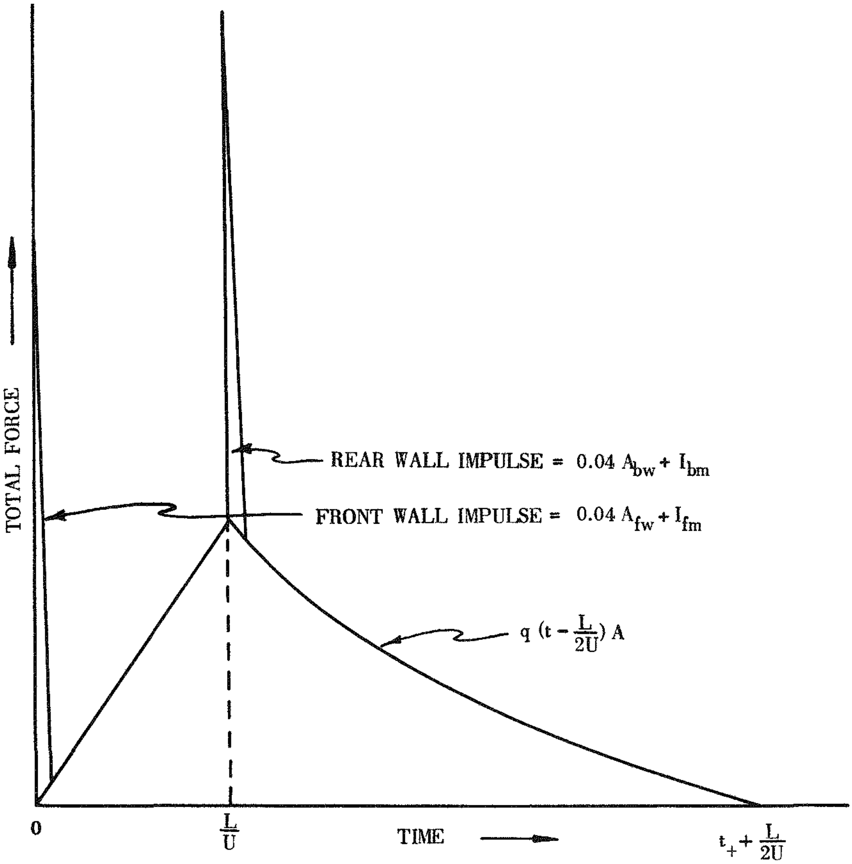

Figure 6.79. Net horizontal loading of an open frame structure.

sections, such as quonset huts and, as a rough approximation, to dome-shaped or spherical structures.

6.81 The discussion presented here is for a cylinder with the direction of propagation of the blast perpendicular to the axis of the cylinder. The pressure-time curves to be developed are, however, those for a semicircular cross section, since a cylinder consists of two such semicylinders with identical loading in each case. The general situation is then as depicted in Fig. 6.81; r is the radius of the cylinder and z represents any point on the surface.

6.82 The reflection coefficient at z varies with the angle α, and for the front part of the structure, i. e., for α between 0° and 90°, the

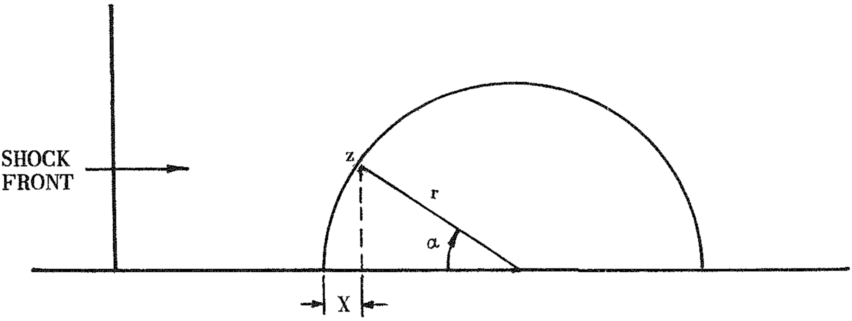

Figure 6.81. Representation of semicylindrical structure.

dependence of the reflected overpressure on the angle α is given in Fig. 6.82a. Here, p is the incident overpressure, p_r is the reflected overpressure at the base, where α is 0°, obtained from Fig. 3.80, and p_{rz} is the value at any arbitrary point z. The drag coefficient also varies with α as shown in Fig. 6.82b, where C_{dz} represents this coefficient at any point z on either the front or back of the semicylindrical structure, i. e., for values of α from 0° to 180°.

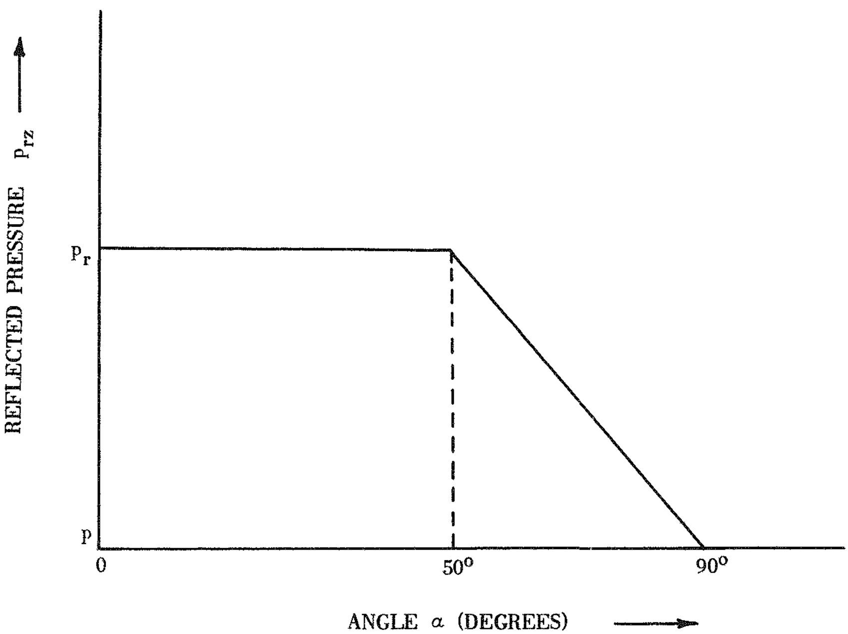

Figure 6.82a. Reflected overpressure versus angle for semicylindrical structure.

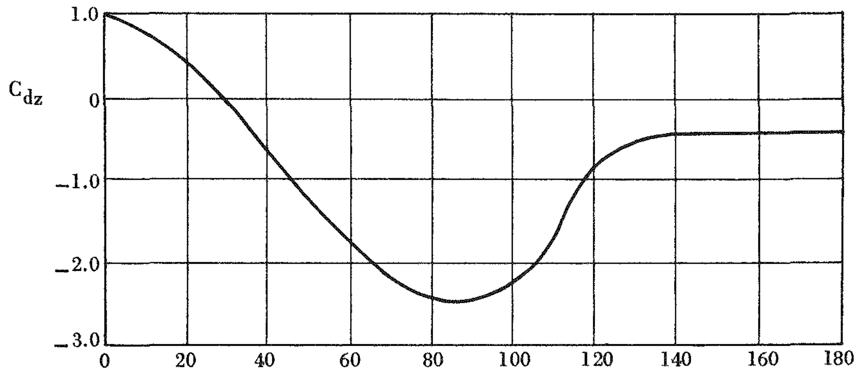

Figure 6.82b. Drag coefficient versus angle for semicylindrical structure.

6.83 Using the information now available, the development of the loading will be considered for (*a*) the front half, (*b*) the back half, and (*c*) the net horizontal force.

6.84 (*a*) *Loading on Front Half* ($\alpha=0°$ *to* $90°$).—The shock front strikes the base of the structure at time $t=0$, and the time of arrival at any point z on the front half is X/U, where,

$$X=r(1-\cos\alpha),$$

as may be seen from Fig. 6.81. The value of the reflected pressure (normal to the surface) at this point is obtained from Fig. 6.82a. The decay time, t_s is $3r/U$ when α is 0° and decreases linearly to zero when α is 90°, as seen in Fig. 6.84a. After time t_s, the pressure (normal to the surface) at any time, t, is given by,

$$\text{Pressure at time } t=p\left(t-\frac{X}{U}\right)+C_{dz}q\left(t-\frac{X}{U}\right).$$

The pressure-time curve at any point z on the front half of the structure is thus of the form shown in Fig. 6.84b.

6.85 (*b*) *Pressure on Back Half* ($\alpha=90°$ *to* $180°$).—The time of arrival of the blast at a point z on the back half is here also equal to X/U, where $X=r(1-\cos\alpha)$. But, instead of the pressure rising sharply, as it does on the front half, there is a finite rise time, t_r, which is zero when $\alpha=90°$ and increases in a linear manner to $2r/U$ when $\alpha=180°$, as seen in Fig. 6.85a. The maximum pressure is thus at-

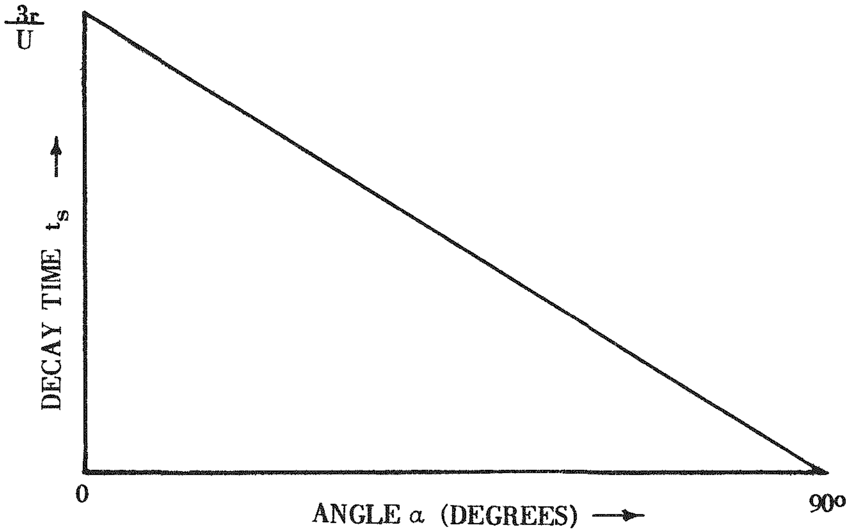

Figure 6.84a. Decay time versus angle for semicylindrical structure.

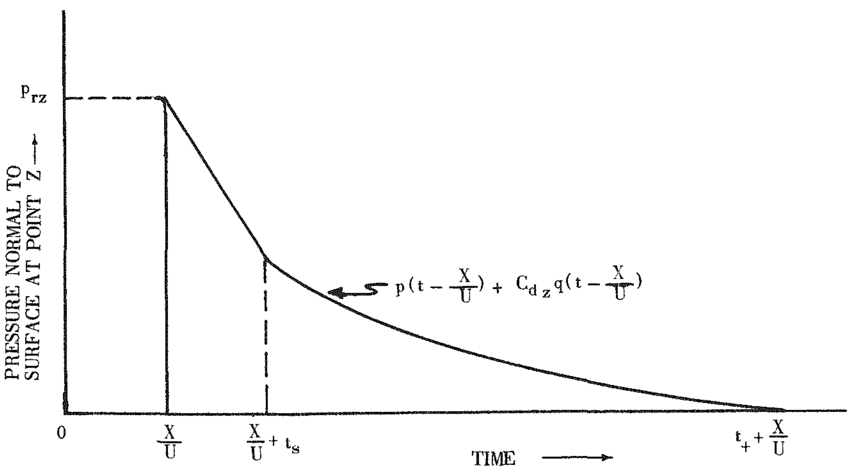

Figure 6.84b. Loading at point on front half of semicylindrical structure.

tained at the time $X/U+t_r$. Subsequently, the decrease in pressure with time is given by,

$$\text{Pressure at time } t = p\left(t-\frac{X}{U}\right) + C_{dz}q\left(t-\frac{X}{U}\right).$$

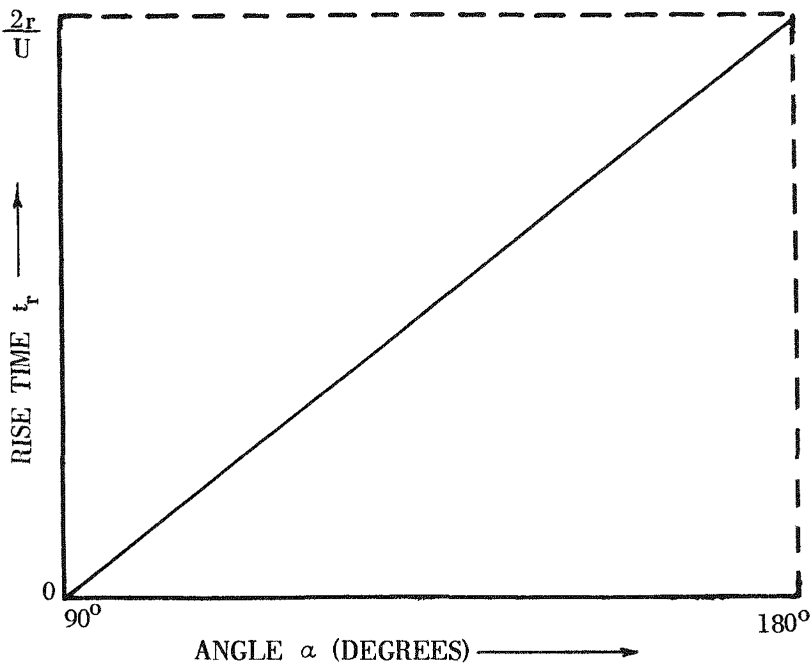

Figure 6.85a. Rise time versus angle for back half of semicylindrical structure.

The development of the loading, as represented by the pressure normal to the surface at any point z on the back half, is indicated in Fig. 6.85b.

6.86 (c) *Net Horizontal Force.*—Since the procedures described above give the loads normal to the surface at any arbitrary point z, the net horizontal loading is not determined by the simple process of subtracting the back loading from that on the front. To obtain the net horizontal loading, it is necessary to sum the horizontal components of the loads over the two areas and then subtract them. In practice, an approximation may be used to obtain the required result, in such cases where the net horizontal loading is considered to be important. It may be pointed out that, in certain instances, especially for large structures, it is the local loading, rather than the net loading, which is the significant criterion of damage.

6.87 In the approximate procedure for determining the net loading, the overpressure loading during the diffraction process is considered to be equivalent to an initial impulse equal to p_rA2r/U, where A is the projected area normal to the direction of the blast propaga-

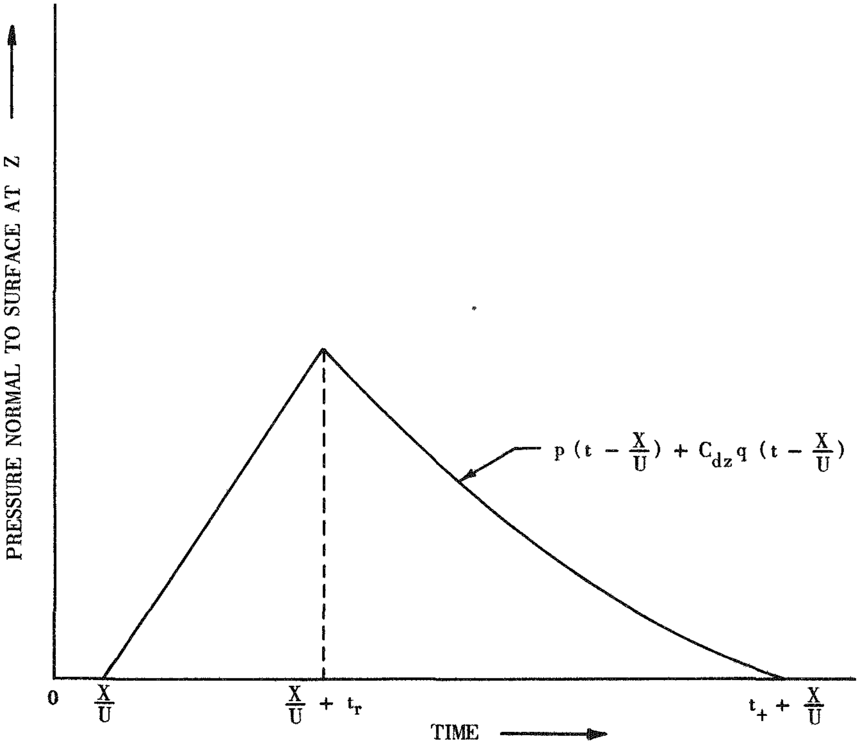

Figure 6.85b. Loading at point on back half of semicylindrical structure.

tion. It will be noted that $2r/U$ is the time taken for the blast front to traverse the structure. The drag coefficient for a single cylinder is about 0.4 in the region of interest, i. e., for overpressures of less than 30 pounds per square inch, postulated earlier. Hence, in addition to the initial impulse, the remainder of the net horizontal loading may be represented by the force 0.4 $q(t)A$, as seen in Fig. 6.87, which applies to a single structure. When a frame is made up of a number of circular elements, the methods used are similar to those for an open frame structure (§ 6.78, *et seq.*) with C_d equal to 0.2.

RESPONSE OF OBJECTS TO AIR BLAST LOADING

Damage to Fixed and Movable Objects

6.88 The response of an object is the motion or deflection it suffers when subjected to loading (§ 3.46). For objects that are fixed to the ground, the response is the movement of one portion of the structure

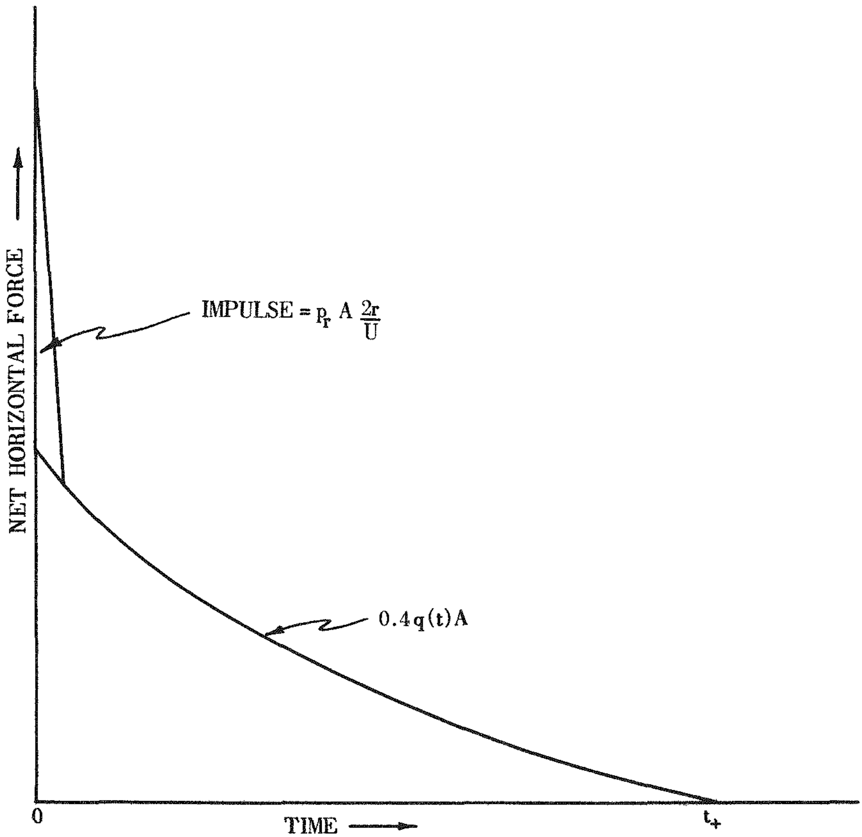

Figure 6.87. Approximate equivalent net horizontal force loading on semicylindrical structure.

relative to some other portion. Movable objects may slide, roll, or tumble over the ground. For fixed objects, any permanent deflection of one part with respect to another is usually considered as damage. Examples of such damage to fixed objects are blown-out windows, collapsed roofs, and dished-in walls.

6.89 The damage to movable objects may be similar, but the cause may be either the direct blast pressure or the manner in which the object set in motion by the blast is brought to rest. The motion of the object may itself cause no damage, but severe damage may result if it strikes another object or the ground. As an example of the damage that may be suffered by a movable object, the response of a vehicle to blast loads may be considered. Relatively high overpressures produce only superficial direct damage, but at the same time

the dynamic pressures cause gross translation of the vehicle resulting in tumbling. While this is occurring, and as a consequence of the tumbling, the major damage takes place, e. g., twisted frame and wheels knocked off.

Factors Affecting Target Response

6.90 A general treatment of the factors which affect the response of an object to blast loading was given in Chapter III. A further discussion of the characteristics of a target that have a significant influence on response will be presented here; these are (1) strength or resistance to deflection, (2) ductility, and (3) mass of target.

6.91 *Strength or Resistance to Deflection.*—The relationship between resistance and deflection will be utilized below to make an analysis of structural response to blast loading. Usually this relationship is determined from static loading and is modified to allow for the rate of strain when the material (or object) is subjected to dynamic loads, as in a nuclear explosion. It may be noted that materials do not build up a maximum resistance until some finite deflection has occurred. However, resistance to overturning of an object in stable equilibrium will, in general, start at a maximum and decrease with increasing deflection.

6.92 *Ductility.*—Ductility, i. e., the ability of materials to deform plastically without failing, is frequently expressed in terms of a yield deflection, i. e., the deflection at which permanent deformation first occurs. Materials with low ductility fail at deflections just a little greater than the yield deflection. High ductility, on the other hand, means that the failure deflection may be 20, 30, or more times the yield deflection. Since ductility is a measure of the energy absorption capacity of a material or structure, it is an important consideration in blast resistance.

6.93 *Mass of Target.*—The mass of the target determines the inertia or magnitude of additional resistance to acceleration of the target. For blast loads of high intensity and short duration it is an important parameter in response analysis. The mass effect is usually expressed in terms of the periods of vibration of the structure. In general, the greater the mass, the greater will be the inertial resistance and the larger the periods of vibration, provided other conditions are more or less equal.

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Analysis of Structural Response

6.94 Once the loading on a structure has been determined, the response can be predicted in principle. But, in many cases, this is not a simple matter because of the extensive mathematics involved. Hence, in order to permit a structural analysis to be made in a reasonable time, some simplification is necessary. For a structure in which the deflection of one point can be related to that of the structure as a whole, the response analysis can be reduced to a relatively simple procedure. If this point may be considered to be free to deflect in one direction only, then a one degree of freedom mass-spring system can be used to represent the response of the structure arising from a single mode of vibration. As a general rule, most of the motion is contributed by the mode corresponding to the lowest (or fundamental) vibration frequency of the structure.

6.95 The major assumption in the following presentation is, therefore, that a system with one degree of freedom will adequately duplicate the given structure. The latter may be treated as a mass-spring system, where the columns of the structure are considered to be springs on which the roof mass rests (Fig. 6.95a). In accordance with the postulate of one degree of freedom, the mass is permitted to deflect in the x-direction only. Thus, under the influence of a force F acting on the roof, the mass is deflected by an amount X (Fig. 6.95b).

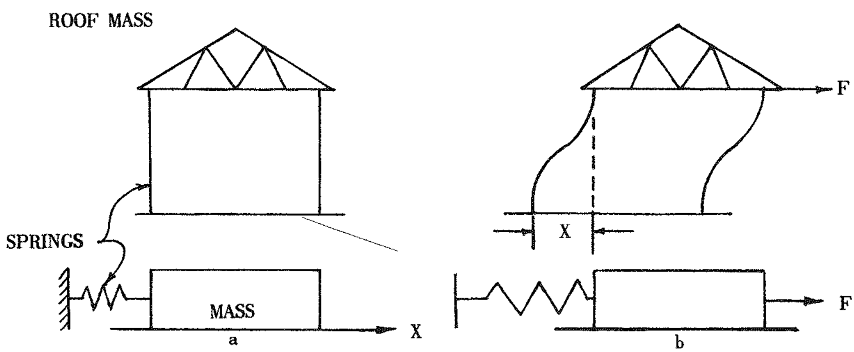

Figure 6.95a. Structure as mass-spring system before deflection.

Figure 6.95b. Structure as mass-spring system when deflected.

6.96 In addition to the structure as a whole, a structural beam or a one-way slab (actually an infinite degree of freedom system) can also be represented as a system of one degree of freedom, by using an

equivalent mass and load. The present discussion is somewhat limited since the methods presented cannot be applied directly to all multi-degree of freedom systems, e. g., a multistory building.

6.97 Another limitation is the assumption that structural materials are deflected beyond the yield point or, in other words, that only large deflections are of interest in connection with the response of structures to blast loads. The methods presented therefore are not intended for use in computing elastic deflections, but rather large plastic deflections.

6.98 A treatment has been developed for calculating the deflection produced in a system of one degree of freedom by a given peak load or, alternatively, of estimating the peak load that will cause a prescribed deflection. For this purpose, three basic data are required, namely, (1) the dynamic resistance-deflection curve of the structure, (2) the fundamental period of vibration, and (3) the blast loading.

Dynamic Resistance-Deflection Curve

6.99 Idealized curves are shown in Fig. 6.99, for the deflection, as a function of the dynamic resistance, of a selected point of the structure (usually the point having the maximum deflection) when subjected to a concentrated load at that point. When the deflection exceeds the yield value, X_e, where the dynamic resistance is Q_e, the curve

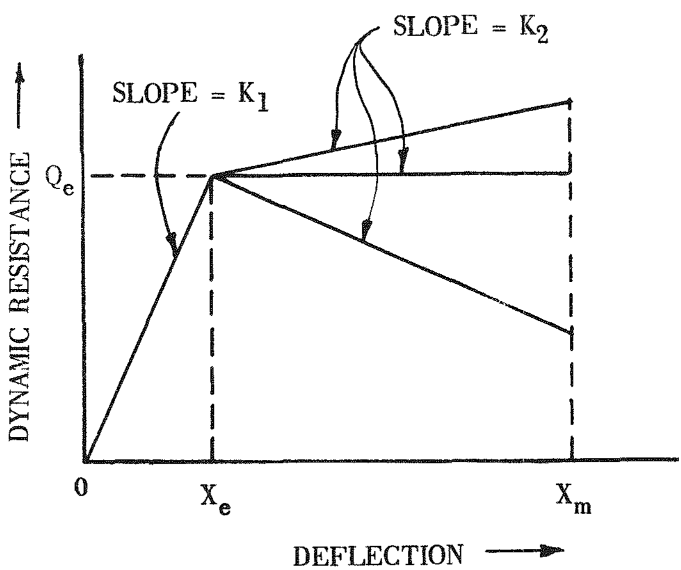

Figure 6.99. Idealized dynamic resistance-deflection curves.

may have one of the three forms indicated, according to the nature of the structure. The slope of the resistance-deflection curve in the elastic region is represented by K_1, whereas in the plastic region it is K_2. The maximum deflection to failure (or deflection prescribed for analysis) is indicated by X_m.

6.100 For reinforced-concrete or steel structures the dynamic resistance curve is derived from the static resistance-deflection curve by adding 20 percent to the values of the dynamic resistance at both X_e and X_m, i. e., at the points representing the yield and maximum deflections, respectively. For structures of masonry, wood, or metal, other than steel, the static resistance curve may be used. If the true static resistance curve is found to be of the form shown by the full curve in Fig. 6.100, it may be approximated by two (dashed) straight lines, the area under the "approximate curve" being equal to that under the "true curve."

Fundamental Period of Vibration

6.101 The fundamental period of vibration, T, of a structure is expressed by

$$T=2\pi\sqrt{\frac{M_e}{K_1}}, \tag{6.101.1}$$

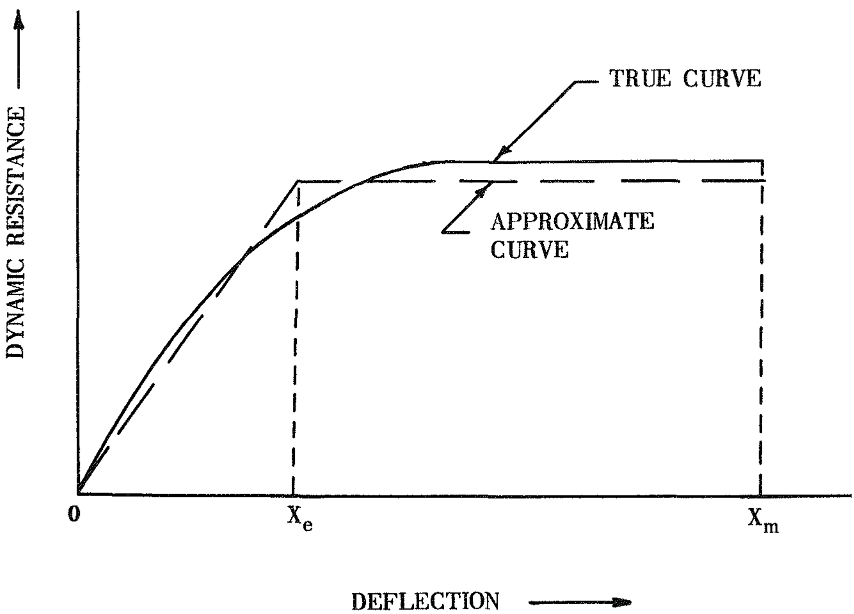

Figure 6.100. True and approximate dynamic resistance-deflection curve.

where K_1 is the slope in the elastic region defined above, and M_e is the equivalent mass of the structure. For a structure consisting of a roof mass supported by columns, as shown in simple form in Fig. 6.95, the equivalent mass, concentrated at the column tops, may be taken as the actual roof mass plus one-half of the mass of the columns, assuming the columns to be fixed at both ends. For structural beams or one-way slabs the equivalent mass is obtained from the total mass by multiplying by the appropriate mass factor given in Table 6.101.

TABLE 6.101

MASS AND LOAD FACTORS

Structure	Mass factor		Load factor
Simply supported beam, uniformly distributed load.	Equivalent mass at center of beam (one degree of freedom).	0. 50	0. 50
Simply supported beam, concentrated center load.	-----do---------------	0. 49	1. 00
Fixed ended beam, uniform load----	-----do---------------	0. 41	0. 50
Fixed ended beam, concentrated center load.	-----do---------------	0. 37	1. 00
Cantilever beam, uniformly distributed load.	Equivalent mass at end of beam (one degree of freedom).	0. 24	0. 40
Cantilever beam, end concentrated load.	-----do---------------	0. 26	1. 00

BLAST LOADING

6.102 For the present purpose, the actual blast loading curve, as developed earlier in this chapter, is replaced by an equivalent force-time curve of the form shown in Fig. 6.102. This consists of an initial impulse, I, plus a linear force-time loading function applied to the point where the mass is assumed to be concentrated. The initial (or peak) force is F, and t_1 is the duration of the equivalent linear load, as indicated in the figure. The peak force in the triangular diagram of Fig. 6.102 is the same as the peak force in the computed distributed loading diagram, and the area of the triangle must be equal to that under the actual loading (force-time) curve. For beams and one-way

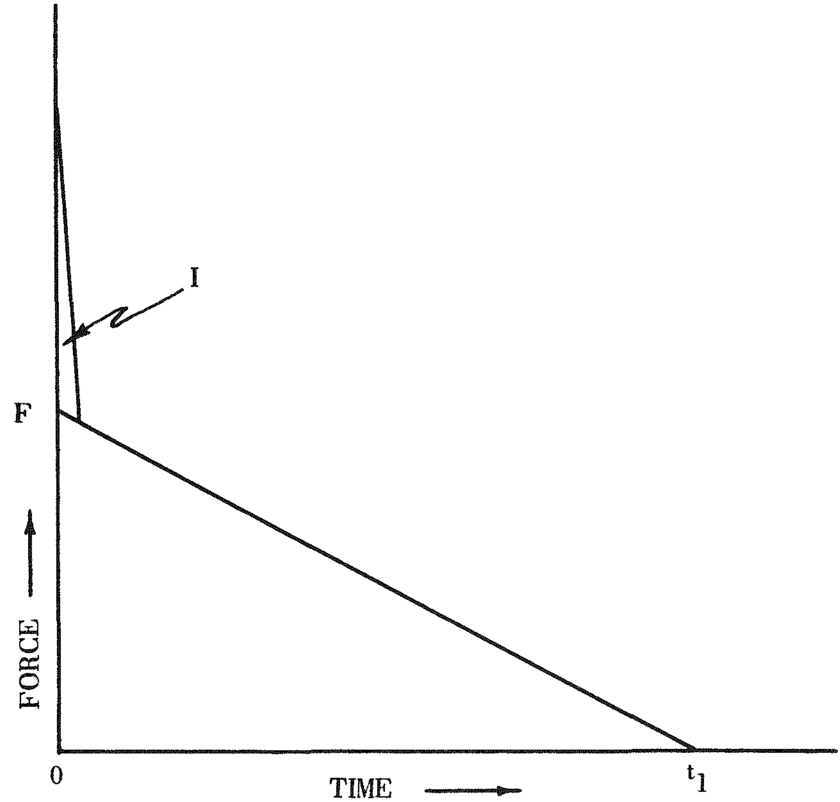

Figure 6.102. Triangular force-time and impulse loading diagram.

slabs, F is equal to the peak force multiplied by the appropriate load factor given in Table 6.101.

6.103 The value of the initial impulse, where it is appropriate, is derived by the methods given above. In many cases, e. g., for large closed or partially open structures, an initial impulse contribution is not computed. For relatively small or open structures, the value of the initial impulse should be determined, although it may turn out to be negligible in magnitude.

6.104 Both the impulse and the linear force function must be changed from distributed loads to concentrated loads at the points where the mass is assumed concentrated. Where buildings have their mass concentrated primarily at floor levels, one-half of the remaining column or wall masses can be carried to each floor level. The distributed blast loads can be concentrated at connections as end reactions computed in the usual manner.

Peak Force-Deflection Relationship

6.105 With the necessary data secured in the manner described above, the solution of the structural response problem is obtained from the equation,

$$\frac{F}{Q_e}=\frac{T}{\pi t_1}(\sqrt{A}-\sqrt{D})+\frac{A-D}{2\frac{X_m}{X_e}\left(1+0.7\frac{T}{t_1}\right)}, \qquad (6.105.1)$$

where

$$A=2\frac{X_m}{X_e}-1+\frac{K_2}{K_1}\left(\frac{X_m}{X_e}-1\right)^2$$

and

$$D=\left(\frac{2\pi I}{Q_e T}\right)^2 \text{ or } D=0 \text{ if } I \text{ is not computed.}$$

For convenience in the application of equation (6.105.1), the various symbols involved, all of which have been defined previously, are given below, together with their usual units:

F=peak force in pounds (see Fig. 6.102)

t_1=duration of equivalent linear loading in seconds (see Fig. 6.102)

Q_e=yield resistance in pounds (see Fig. 6.99)

T=fundamental period of vibration in seconds (see equation (6.101.1))

I=initial impulse in pound-seconds (see Figs. 6.79, 6.87, and 6.102)

X_e=yield deflection in any units (see Fig. 6.99)

X_m=maximum (or prescribed) deflection in same units as X_e (see Fig. 6.99)

K_1=slope of dynamic resistance-deflection curve in elastic region (see Fig. 6.99)

K_2=slope of dynamic resistance-deflection curve in plastic region (see Fig. 6.99).

6.106 There are two general types of problems which may be solved with the aid of equation (6.105.1). If the load is prescribed, e. g., a given distance from an explosion of a specified yield, so that F may be regarded as known, the corresponding deflection, X_m, can be determined. Alternatively, if the maximum (or prescribed) deflection,

X_m, is given, the corresponding value of F can be calculated. In either case, the solution must be approached by a series of approximations.

6.107 If the load is specified, so that F and t_1 may both be regarded as known, a provisional value of X_m must first be estimated and then checked by means of equation (6.105.1). A new value is then tried, and so on, until agreement of the two sides is obtained. On the other hand, if a particular deflection, X_m, is decided upon to represent the degree of damage that can be tolerated or that is not to be exceeded, the calculation of F is somewhat more difficult, since t_1 is also unknown and this is dependent upon F. It is necessary, therefore, to guess a linear function for the variation of the force with time, so as to give t_1. With this, an approximate value of F is determined from equation (6.105.1), and a check of the guessed function is then made. This permits a new estimate of t_1, and the process is repeated until a satisfactory solution is obtained.

6.108 The use of the procedure just described can involve an error when the dynamic resistance curve shows the structure to be unstable, i. e., when K_2 is negative. The solution to a problem of determining the value of F to produce a deflection X_m may then imply that a greater force F is required for a smaller value of X_m. It is necessary, therefore, to check this possibility. For cases in which K_2 is negative, F is first determined for a certain X_m, say 2 feet, then F is redetermined for a somewhat smaller value of X_m, say 1.8 feet, which is greater than X_e but close to the original X_m. If the second value of F is greater than the first, the calculations must be continued to determine the maximum value of F, called F_m, which is associated with X_m. For any greater value of the deflection X_m, the force F_m is still required.

7.16 It is because of the compensation due to multiple scattering, therefore, that the total amount of energy from a nuclear explosion falling upon unit area at a given distance may not be greatly dependent upon the visibility range, within certain limits. It should be noted that this general conclusion will apply only if the atmosphere is reasonably clear, that is, in the absence of rain, fog, or dense industrial haze. If these special conditions exist, however, only a small proportion of the thermal radiation escapes scattering. The considerable loss in the directly transmitted radiation cannot now be compensated by multiple scattering. There is consequently a definite decrease in the radiant energy received at a specified distance from the explosion. Another exceptional case, considered below, is when the explosion occurs below a cloud layer.

7.17 Attention should also be drawn to the limitation concerning distance mentioned at the end of § 7.13, namely, that the thermal radiation attenuation is somewhat independent of the atmospheric conditions only at distances from the explosion less than half the visibility range. At greater distances, more of the radiant energy is lost as the atmospheric visibility becomes less. In these circumstances, therefore, the supposition that the energy attenuation is independent of the visibility leads to estimates of the thermal energy that are too high. From the standpoint of protection, such estimates are preferable to those which err in being too low.

Effect of Smoke and Fog

7.18 In the event of an air burst occurring above a layer of dense cloud, smoke, or fog, an appreciable portion of the thermal radiation will be scattered upward from the top of the layer. This scattered radiation may be regarded as lost, as far as a point on the ground is concerned. In addition, most of the radiation which penetrates the layer will be scattered, and very little will reach the given point by direct transmission. These two effects will result in a substantial decrease in the amount of thermal energy reaching a ground target covered by fog or smoke, from a nuclear explosion above the layer.

7.19 Artificial white (chemical) smoke acts just like fog in attenuating thermal radiation. A dense smoke screen between the point of burst and a given target can reduce the thermal radiation energy to as little as one-tenth of the amount which would otherwise be received at the target. Smoke screens would thus appear to provide the possi-

bility of protection against thermal radiation from a nuclear explosion.

7.20 It is important to understand that the decrease in thermal radiation by fog and smoke, will be realized only if the burst point is above or, to a lesser extent, within the fog (or similar) layer. If the explosion should occur in moderately clear air beneath a layer of cloud, or fog, some of the radiation which would normally proceed outward into space will be scattered back to earth. As a result, the thermal energy received will actually be greater than for the same atmospheric transmission conditions without a cloud or fog cover.

Effect of Shielding

7.21 Unless scattered, thermal radiation from a nuclear explosion, like ordinary light in general, travels in straight lines from its source, the ball of fire. Any solid, opaque material, such as a wall, a hill, or a tree, between a given object and the fireball will thus act as a shield and provide protection from thermal radiation. Some instances of such shielding, many of which were observed after the nuclear explosions in Japan, will be described later. Transparent materials, on the other hand, such as glass or plastics, allow thermal radiation to pass through only slightly attenuated.

7.22 A shield which merely intervenes between a given target and the ball of fire, but does not surround the target, may not be entirely effective under hazy atmospheric conditions. A large proportion of the thermal radiation received, especially at considerable distances from the explosion, has undergone scattering and will arrive from all directions, not merely that from the point of burst. This situation should be borne in mind in connection with the problem of thermal radiation shielding.

Type of Burst

7.23 The foregoing discussion has referred in particular to thermal radiation from a nuclear air burst. For other types of burst the general effects are the same, although they differ in degree. For a surface burst, when the ball of fire actually touches the earth or water, the proportion of the explosion energy appearing as thermal radiation will be less than for an air burst. This is due partly to the fact that a portion of the thermal radiation is absorbed by the earth (or water). Less of the thermal energy is lost in this manner as the height of burst is increased.

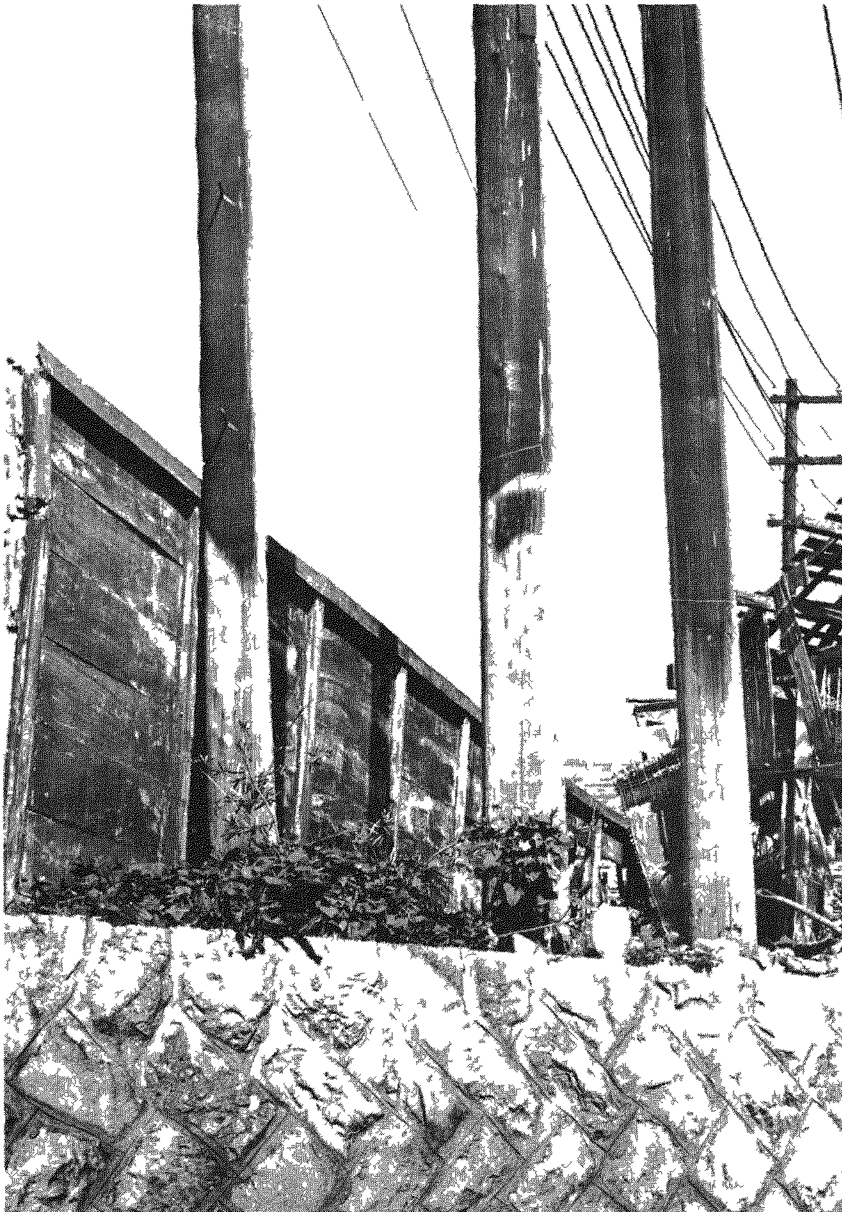

Figure 7 73b Nagasakı) by a fence Flash burns on wooden poles (1 17 miles from ground zero at The uncharred portions were protected from thermal radiation

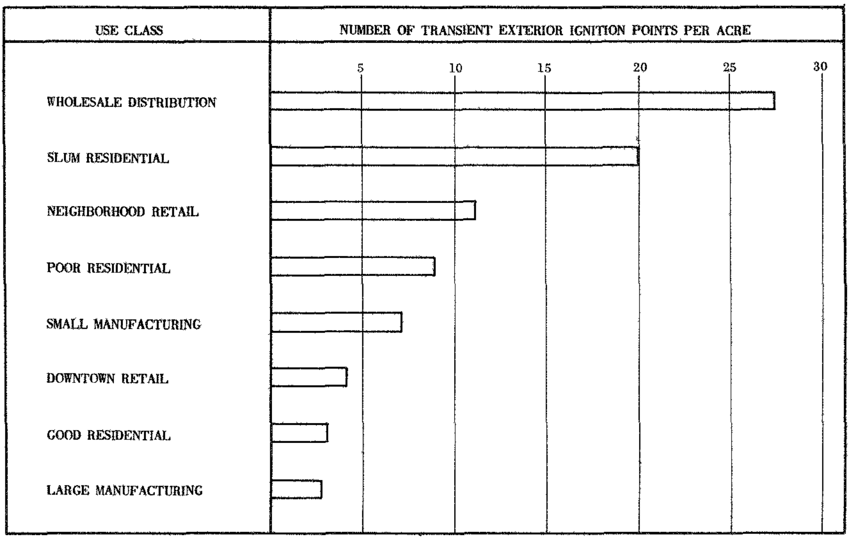

Figure 7.80. Frequency of exterior ignition points for various areas in a city.

number of large cities in the United States. It is seen that the density of ignition points is greatest in wholesale distribution and slum residential areas, and is least in good residential and large manufacturing areas.[5] Paper was the commonest ignitable material found everywhere except in downtown retail areas where awnings represented the major source of fire.

7.81 The density of ignition points provides some indication of the chance of fires being started under ideal weather conditions. But the results in Fig. 7.80 are by themselves not sufficient to permit an estimate to be made of the number of significant fires that will actually result. In the first place, at locations closer to ground zero, where the thermal energy exceeds about 12 calories per square centimeter, almost all the ignitable materials will actually flame (Table 7.65). On the other hand, at greater distances, only those most easily ignitable will catch fire. Further, the formation of a significant fire, capable of spreading, will require appreciable quantities of combustible material close by, and this may not always be available.

7.82 The fact that accumulations of ignitable trash close to a wooden structure represent a real fire hazard was demonstrated at the nuclear tests carried out in Nevada in 1953. In these tests, three miniature wooden houses, each having a yard enclosed with a wooden

[5] The area types are in accordance with the classification used by the U. S. Bureau of Census.

fence, were exposed to 12 calories per square centimeter of thermal radiation. One house, at the left of Fig. 7.82, had weathered siding showing considerable decay, but the yard was free from trash. The next house also had a clean yard and, further, the exterior siding was well maintained and painted. In the third house, at the right of the photograph, the siding, which was poorly maintained, was weathered, and the yard was littered with trash.

7.83. The state of the three houses after the explosion is seen in Fig. 7.83. The third house, at the right, soon burst into flame and was burned to the ground. The first house, on the left, did ignite but it did not burst into flame for 15 minutes. The well maintained house in the center with the clean yard suffered scorching only. It is of interest to recall that the wood of a newly erected white-painted house exposed to about 25 calories per square centimeter was badly charred but did not ignite (Fig. 7.34b).

7.84 The value of fire-resistive furnishing in decreasing the number of ignition points was also demonstrated in the 1953 tests. Two identical, sturdily constructed houses, each having a window 4 feet by 6 feet facing the point of burst, were erected where the thermal radiation exposure was 17 calories per square centimeter. One of the houses contained rayon drapery, cotton rugs, and clothing, and, as was expected, it burst into flame immediately after the explosion and burned completely. In the other house, the draperies were of vinyl plastic, and rugs and clothing were made of wool. Although more ignition occurred, the recovery party, entering an hour after the explosion, was able to extinguish fires.

7.85 There is another point in connection with the initiation of fires by thermal radiation that needs consideration. This is the possibility that the flame resulting from the ignition of a combustible material may be subsequently extinguished by the blast wind. It was thought that there was evidence for such an effect from an observation made in Japan (§ 7.92), but this may have been an exceptional case. The matter has been studied, both in connection with the effects in Japan and at various nuclear tests, and the general conclusion is that the blast wind has no significant effect in extinguishing fires (see § 7.93).

Spread of Fires

7.86 The spread of fires in a city, depends upon a variety of conditions, e. g., weather, terrain, and closeness and combustibility of the buildings. A detailed review of large-scale fires has shown, however, that if other circumstances are more-or-less the same, the most

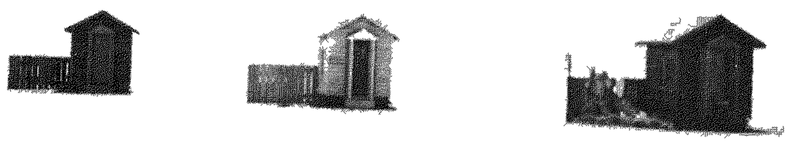

Figure 7 82 Wooden test houses before exposure to a nuclear explosion, Nevada Test Site

Figure 7 83 Wooden test houses after exposure to the nuclear explosion

important criterion of the probability of fire spread is the distance between buildings. It is evident, from general considerations, that the lower the building density or "built-upness" of an area, the less will be the probability that fire will spread from one structure to another. Further, the larger the spaces between buildings the greater the chances that the fire can be extinguished.

7.87 The curve in Fig. 7.87 gives a rough idea of how the probability of fire spread, expressed as a percentage, depends upon the average distance between buildings in a city. The results will be dependent, to some extent, upon the types of structures involved, e. g., whether they are fire-resistive or not, as well as upon the damage caused by the blast wave (§ 7.79). It should be noted that Fig. 7.87 applies to fire spread accompanying a nuclear explosion, when a large number of small fires are started directly by thermal radiation and indirectly in other ways.

7.88 Another aspect of fire spread is the development of mass fires in a forest following primary ignition of dried leaves, grass, and rotten wood by the thermal radiation. Some of the factors which will influence the growth of such fires are the moisture content of the trees,

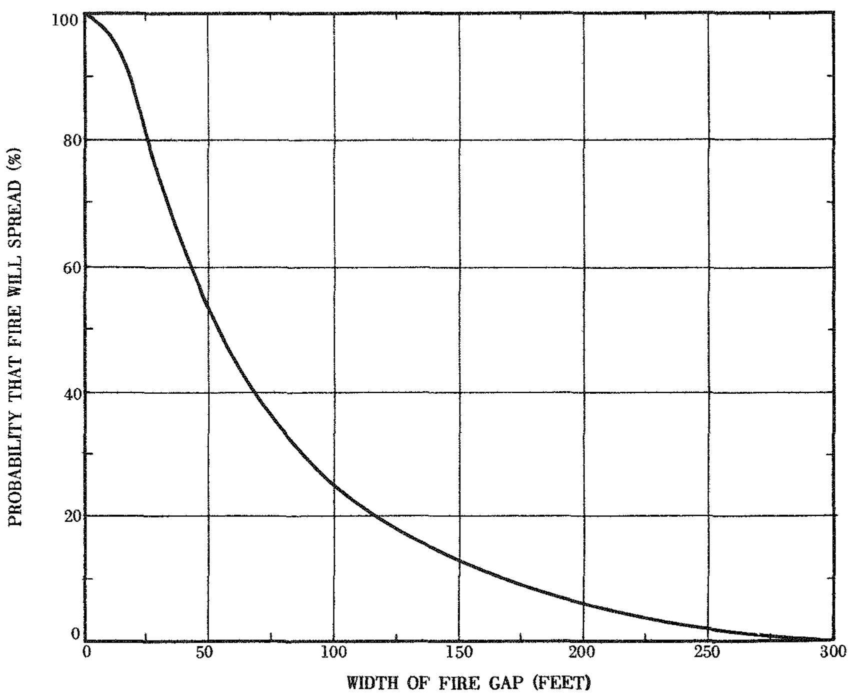

Figure 7.87. Width of gap and probability of fire spread.

topography, and meteorological conditions. Low atmospheric humidity, strong winds, and steep terrain favor the development of forest fires. In general, a deciduous forest, particularly when in leaf, may be expected to burn less rapidly and with less intensity than a forest of coniferous trees. Green leaves and the trunks of trees would act as shields against thermal radiation, so that the number of points at which ignition occurs in a forest may well be less than would appear at first sight.

INCENDIARY EFFECTS IN JAPAN

The Nuclear Bomb as an Incendiary Weapon

7.89 The incendiary effects of a nuclear explosion do not present any especially characteristic features. In principle, the same over-all result, as regards destruction by fire and blast, might be achieved by the use of conventional incendiary and high-explosive bombs. It has been estimated, for example, that the fire damage to buildings and other structures suffered at Hiroshima could have been produced by about 1,000 tons of incendiary bombs distributed over the city. It can be seen, however, that since this damage was caused by a single nuclear bomb of only 20 kilotons energy yield, nuclear weapons are capable of causing tremendous destruction by fire, as well as by blast.

7.90 Evidence was obtained from the nuclear explosions over Japan that the damage by fire is much more dependent upon local terrain and meteorological conditions than are blast effects. At both Hiroshima and Nagasaki the distances from ground zero at which particular types of blast damage were experienced were much the same. But the range of incendiary effects was quite different. In Hiroshima, for example, the total area severely damaged by fire, about 4.4 square miles, was roughly four times as great as in Nagasaki. One contributory cause was the irregular layout of Nagasaki as compared with Hiroshima; also greater destruction could probably have been achieved by a change in the point of burst. Nevertheless, an important factor was the difference in terrain, with its associated building density. Hiroshima was relatively flat and highly built up, whereas Nagasaki had hilly portions near ground zero that were bare of structures.

Origin and Spread of Fires in Japan

7.91 Definite evidence was obtained from Japanese observers that the thermal radiation caused thin, dark cotton cloth, such as the

black-out curtains that were in common use during the war, thin paper, and dry, rotted wood to catch fire at distances up to 3,500 feet (0.66 mile) from ground zero (about 35 calories per square centimeter). It was reported that a cedar bark roof farther out was seen to burst into flame, apparently spontaneously, but this was not definitely confirmed. Abnormal enhanced amounts of radiation, due to reflection, scattering, and focusing effects, might have caused fires to originate at isolated points (Fig. 7.91).

7.92 Interesting evidence of the ignition of sound wood was found about a mile from ground zero at Nagasaki, where the thermal energy was approximately 15 calories per square centimeter. A light piece of wood, similar to the flat side of an orange crate, had its front surface charred. In addition, however, blackening was observed through cracks and nail holes, where the thermal radiation would not have penetrated, and also around the edges adjoining the charred surface. A possible explanation is that the exposed surface of the wood had actually ignited, due to the heat from the thermal radiation, and the flames had spread through the cracks and holes around the edges for several seconds, before they were extinguished by the blast wind.

7.93 From the evidence of charred wood found at both Hiroshima and Nagasaki, it was originally concluded that such wood had actually been ignited by thermal radiation and that the flames were subsequently extinguished by the blast. But it now seems more probable that, apart from some exceptional instances, such as that just described, there was no actual ignition of the wood. The absorption of the thermal radiation caused charring in sound wood but the temperatures were generally not high enough for ignition to occur (§ 7.34). Rotted and checked wood and excelsior, however, have been known to burn completely, and the flame is not greatly affected by the blast wave.

7.94 It is not known to what extent thermal radiation contributed to the initiation of fires in the nuclear bombings in Japan. It is possible that, up to a mile or so from ground zero, some fires may have originated from secondary causes, such as upsetting of stoves, electrical short-circuits, broken gas lines, and so on, which were a direct effect of the blast wave. A number of fires in industrial plants were initiated by furnaces and boilers being overturned, and by the collapse of buildings on them.

7.95 Once the fires had started, there were several factors, directly related to the destruction caused by the nuclear explosion, that influenced their spreading. By breaking windows and blowing in or

damaging fire shutters (Fig. 7.95), by stripping wall and roof sheathing, and collapsing walls and roofs, the blast made many buildings more vulnerable to fire. Noncombustible (fire-resistive) structures were often left in a condition favorable to the internal spread of fires by damage at stairways, elevators, and in firewall openings, as well as by the rupture and collapse of floors and partitions (Fig. 4.85d).

Figure 7.95. Fire shutters in building blown in or damaged by the blast; shutter at center probably blown outward by blast passing through building (0.57 mile from ground zero at Hiroshima).

7.96 On the other hand, when combustible frame buildings were blown down, they did not burn as rapidly as they would have done had they remained standing. Further, the noncombustible debris produced by the blast frequently covered and prevented the burning of combustible material. There is some doubt, therefore, whether, on the whole, the effect of the blast was to facilitate or to hinder the development of fires at Hiroshima and Nagasaki.

7.97 Although there were firebreaks, both natural, e. g., rivers and open spaces, and artificial, e. g., roads and cleared areas, in the Jap-

anese cities, they were not very effective in preventing the fires from spreading. The reason was that fires often started simultaneously on both sides of the firebreaks, so that they could not serve their intended purpose. In addition, combustible materials were frequently strewn across the firebreaks and open spaces, such as yards and street areas, by the blast, so that they could not prevent the spread of fires. Nevertheless, there were a few instances where firebreaks assisted in preventing the burn-out of some fire-resistive buildings.

7.98 One of the important aspects of the nuclear bomb attacks on Japan was that, in the large area that suffered simultaneous blast damage, the fire departments were completely overwhelmed. It is true that the fire-fighting services and equipment were poor by American standards, but it is doubtful if much could have been achieved, under the circumstances, by more efficient fire departments. At Hiroshima, for example, 70 percent of the fire-fighting equipment was crushed in the collapse of fire houses, and 80 percent of the personnel were unable to respond. Even if men and machines had survived the blast, many fires would have been inaccessible because of the streets being blocked with debris. For this reason, and also because of the fear of being trapped, a fire company from an area which had escaped destruction was unable to approach closer than 6,600 feet (1.25 miles) from ground zero at Nagasaki. It was almost inevitable, therefore, that all buildings within this range would be destroyed.

7.99 Another contributory factor to the destruction by fire was the failure of the water supply in both Hiroshima and Nagasaki. The pumping stations were not largely affected, but serious damage was sustained by distribution pipes and mains, with a resulting leakage and drop in available water pressure. Most of the lines above ground were broken by collapsing buildings and by heat from the fires which melted the pipes. Some buried water mains were fractured and others were broken due to the collapse or distortion of bridges upon which they were supported (§4.113).

Fire Storm in Hiroshima

7.100 About 20 minutes after the detonation of the nuclear bomb at Hiroshima, there developed the phenomenon known as "fire storm." This consisted of a wind which blew toward the burning area of the city from all directions, reaching a maximum velocity of 30 to 40 miles per hour about 2 to 3 hours after the explosion, decreasing to light or moderate and variable in direction about 6 hours after. The

wind was accompanied by intermittent rain, light over the center of the city and heavier about 3,500 to 5,000 feet (0.67 to 0.95 mile) to the north and west. Because of the strong inward draft at ground level, the fire storm was a decisive factor in limiting the spread of the fire beyond the initial ignited area. It accounts for the fact that the radius of the burned-out area was so uniform in Hiroshima and was not much greater than the range in which fires started soon after the explosion. However, virtually everything combustible within this region was destroyed.

7.101 It should be noted that the fire storm is by no means a special characteristic of the nuclear bomb. Similar fire storms have been reported as accompanying large forest fires in the United States, and especially after incendiary bomb attacks in both Germany and Japan during World War II. The high winds are produced largely by the updraft of the heated air over an extensive burning area. They are thus the equivalent, on a very large scale, of the draft of a chimney under which a fire is burning. The rain associated with a fire storm is apparently due to the condensation of moisture on particles from the fire when they reach a cooler area.

7.102 The incidence of fire storms is dependent on the conditions existing at the time of the fire. Thus, there was no such definite storm over Nagasaki, although the velocity of the southwest wind, blowing between the hills, increased to 35 miles an hour when the conflagration had become well established, perhaps about 2 hours after the explosion. This wind tended to carry the fire up the valley in a direction where there was nothing to burn. Some 7 hours later, the wind had shifted to the east and its velocity had dropped to 10 to 15 miles per hour. These winds undoubtedly restricted the spread of fire in the respective directions from which they were blowing. The small number of dwellings exposed in the long narrow valley running through Nagasaki probably did not furnish sufficient fuel for the development of a fire storm as compared to the many buildings on the flat terrain at Hiroshima.

TECHNICAL ASPECTS OF THERMAL RADIATION[6]

Spectral Distribution of Energy from Ball of Fire

7.103 If it can be assumed that the ball of fire in a nuclear explosion, like the sun, behaves rather like a black body, i. e., as a perfect radiator, the distribution of the thermal radiation energy over the

[6] The remaining sections of this chapter may be omitted without loss of continuity.

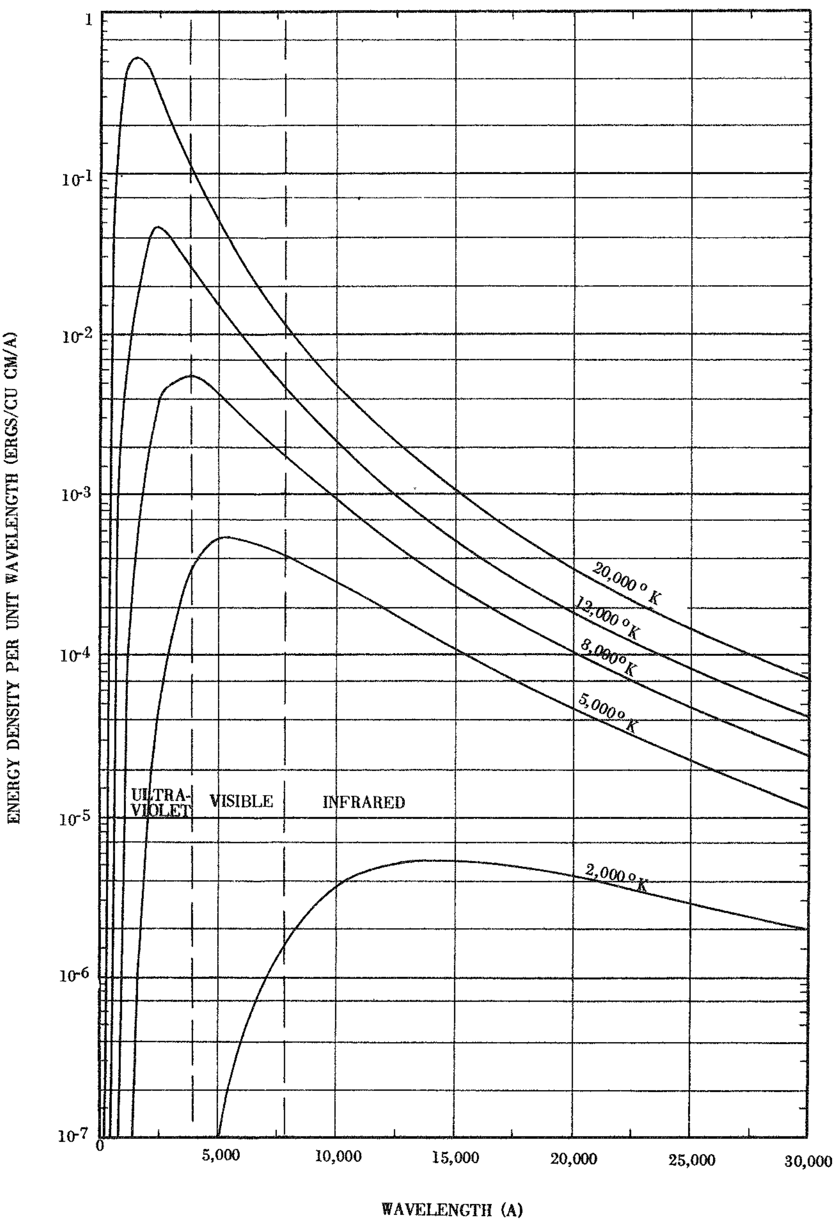

Figure 7.104. Energy density per unit wave length of radiations of various wave lengths.

spectrum can be related to the surface temperature by Planck's radiation equation. If $E_\lambda d\lambda$ denotes the energy density, i. e., energy per unit volume, in the wave length interval λ to $\lambda+d\lambda$, then,

$$E_\lambda=\frac{8\pi hc}{\lambda^5}\cdot\frac{1}{e^{hc/\lambda kT}-1}, \qquad (7.103.1)$$

where c is the velocity of light, h is Planck's quantum of action, k is Boltzmann's constant, i. e., the gas constant per molecule, and T is the absolute temperature.

7.104 From the Planck equation it is possible to calculate the energy density of the thermal radiation from a nuclear explosion over a range of wave lengths for any specified temperature. The results obtained for several temperatures are shown by the curves in Fig. 7.104. It will be apparent that at temperatures exceeding about 8,000° K., such as is the case during most of the first radiation pulse from the ball of fire, i. e., prior to the first temperature minimum, much of the thermal energy emitted lies in the short wave length (ultraviolet) region of the spectrum.

7.105 As the temperature of the black-body radiator decreases, the wave length at which the energy density is a maximum is seen to move to the right, i. e., to regions of higher wave length. An expression for the wave length for maximum energy density, λ_m, can be obtained by differentiating equation (7.103.1) with respect to wave length and equating the result to zero. It is then found that

$$\lambda_m=\frac{A}{T}, \qquad (7.105.1)$$

where A is a constant, equal to 0.2897 angstrom-degree K. Hence, the wave length for maximum energy density is inversely related to the absolute temperature.

7.106 From the known value of A, it can be calculated that the maximum energy density of thermal radiation just falls into the visible region of the spectrum at a temperature of about 7,600° K. This happens to be very close to the maximum surface temperature of the ball of fire after the minimum, i. e., during the second radiation pulse (Fig. 2.92). Since the temperature does not exceed 7,600° K. and the average is considerably less, it is evident that most of the radiant energy emitted in the second pulse consists of visible and infrared rays, with very little in the ultraviolet region of the spectrum.

Thermal Energy from Ball of Fire

7.107. For the present purpose, the total rate of emission of thermal radiation energy from the ball of fire is more significant than the

distribution of radiation density. According to the Stefan-Boltzmann law for black-body radiation, the flux (or intensity) of radiant energy, ϕ, i. e., the amount of energy passing through 1 square centimeter of surface of a black body per second, is related to the absolute temperature, T, by the equation,

$$\phi = \sigma T^4, \qquad (7.107.1)$$

where σ is a constant. The value of ϕ can also be obtained by integration of the Planck equation (7.103.1), at constant temperature, over the whole range of wave lengths, from zero to infinity. It is then found that

$$\begin{aligned}\sigma &= 2\pi^5 k^4/15h^3c^2 \\ &= 1.38\times 10^{-12}\text{cal}/(\text{cm}^2)\,(\text{sec})\,(\text{deg}^4).\end{aligned}$$

With σ known, the total radiant energy intensity from the ball of fire behaving as a black body can be readily calculated for any required temperature.

7.108 According to equation (7.107.1), the intensity of the radiation emitted from the ball of fire at any temperature is proportional to the fourth power of that temperature on the absolute scale. Since the surface temperatures are very high during the first radiation pulse, the rate of energy emission (per unit area), mainly in the ultraviolet region, will also be high. However, because of the short duration of the initial pulse, the total *quantity* of energy emitted is relatively small. In any case, most of what is emitted is absorbed and scattered by the atmosphere before it travels any appreciable distance from the fireball.

7.109 In accordance with the definition of radiation flux, ϕ, given in § 7.107, it follows that the total rate of emission of radiant energy from the ball of fire can be obtained upon multiplying the expression in equation (7.107.1) by the area. If R is the radius of the fireball, its area is $4\pi R^2$, so that the rate of thermal energy emission is $\sigma T^4 \times 4\pi R^2$. This is the same as the thermal power, since power is defined as the rate of production (or expenditure) of energy. Representing this quantity by the symbol P, it follows that

$$\begin{aligned}P &= 4\pi\sigma T^4 R^2 \\ &= 1.71\times 10^{-11} T^4 R^2 \text{ calories per second,}\end{aligned}$$

where T is in degrees Kelvin and R is in centimeters. Alternatively, if the radius, R, is expressed in feet, then,

$$P = 1.59\times 10^{-8} T^4 R^2 \text{ calories per second.} \qquad (7.109.1)$$

7.110 The results of numerous tests have shown that the ball of fire

does not, in fact, behave as a perfect radiator. This is due to a number of factors. The surface temperature during the first radiation pulse is modified by the disturbed air immediately around the fireball and, at later times, the temperature is not that of the surface but the result of radiation some distance inside the fireball. The radius of the ball of fire during the second thermal pulse is very difficult to determine because the surface of the luminous ball of fire becomes very diffuse. Since the radii and surface temperatures will depend on the energy yield of the explosion, a different curve will be obtained for every value of the yield. However, it is possible to generalize the results, by means of scaling laws, so that a curve applicable to the second pulse for all energy yields can be obtained from a single set of calculations.

7.111 Actually the power, P, is measured directly as a function of time, t, for each explosion. However, instead of plotting P versus t, a curve is drawn of the scaled power, i. e., P/P_{max}, versus the scaled time, i. e., t/t_{max}, where P_{max} is the maximum value of the thermal power, corresponding to the temperature maximum in the second pulse, and t_{max} is the time at which this maximum is attained. The resulting (left scale) curve, shown in Fig. 7.111 is then of general applicability, irrespective of the yield of the explosion.

7.112 In order to make the power-time curve specific for any particular explosion energy yield, it is necessary to know the appropriate values of P_{max} and t_{max}. These are related to the yield, W kilotons, in the following manner:

$$P_{max}=4W^{1/2} \text{ kilotons per second,}$$

and

$$t_{max}=0.032W^{1/2} \text{ seconds.}$$

The application of these equations is illustrated in the example facing Fig. 7.111.

7.113 The amount of thermal energy, E, emitted by the ball of fire up to any specified time can be obtained from the area under the curve of P versus t up to that time. The result, expressed in percent as E/E_{tot} versus t/t_{max}, is shown by the second curve (right scale) in Fig. 7.111. The quantity E_{tot} is the total thermal energy emitted by the ball of fire; this is related to the total energy yield of the explosion, W kilotons, by the expression,

$$E_{tot} \text{ (kilotons)} = \tfrac{1}{3}\, W, \qquad (7.113.1)$$

derived from measurements made at a number of test explosions. This equation gives the thermal energy in terms of kilotons of TNT

(Text continued on page 334.)

The curves show the variation with the scaled time, t/t_{max}, of the scaled fireball power, P/P_{max} (left ordinate) and of the percent of the total thermal energy emitted, E/E_{tot} (right ordinate).

Scaling. In order to apply the data in Fig. 7.111 to an explosion of any energy, W kilotons, the following expressions are used:

$$P_{max}=4\ W^{1/2} \text{ kilotons per second}$$

$$t_{max}=0.032\ W^{1/2} \text{ seconds.}$$

$$E_{tot}=\tfrac{1}{3}\ W \text{ kilotons,}$$

where

t_{max}=time after explosion for temperature maximum in second thermal pulse,

P_{max}=maximum rate (at t_{max}) of emission of thermal energy from fireball,

and

E_{tot}=total thermal energy emitted by fireball.

Example

Given: A 500 KT burst.

Find: (*a*) The rate of emission of thermal energy, (*b*) the amount of thermal energy emitted, at 2 seconds after the explosion.

Solution: Since W is 500 KT, the value of $W^{1/2}$ is 22.4, so that $t_{max}=0.032\times22.4=0.72$ second, and the scaled time at 2 seconds after the explosion is

$$t/t_{max}=2.0/0.72=2.8.$$

(*a*) From Fig. 7.111, the value of P/P_{max} at this scaled time is 0.26, and since $P_{max}=4\times22.4=90$ kilotons per second, it follows that,

$$P=0.26\times90=23 \text{ kilotons per second}$$
$$=23\times10^{12} \text{ calories per second.} \quad \textit{Answer}$$

(*b*) At the scaled time of 2.8, the value of E/E_{tot} from Fig. 7.111 is 58 percent, i. e., 0.58.

$$E_{tot}=\tfrac{1}{3}\times500=167 \text{ kilotons}$$

Hence,

$$E=0.58\times167=97 \text{ kilotons}$$
$$=97\times10^{12} \text{ calories.} \quad \textit{Answer}$$

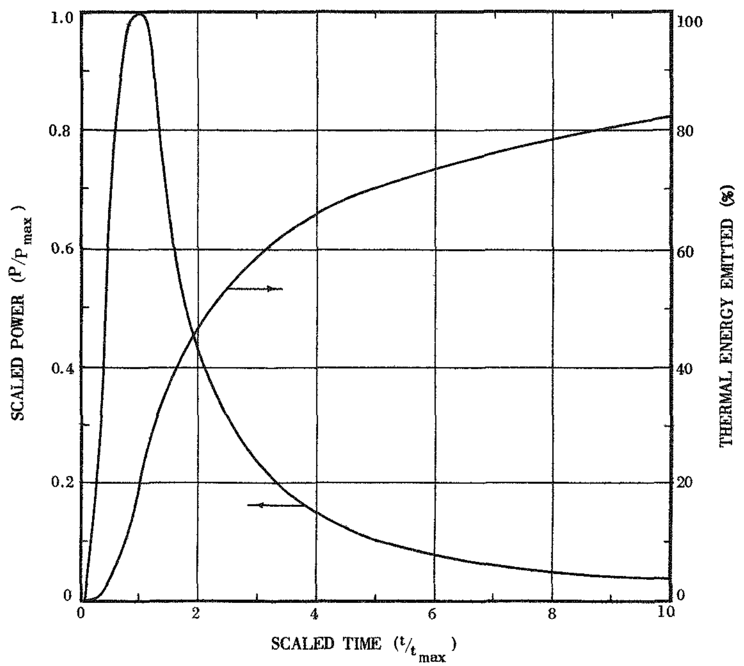

Figure 7.111. Scaled fireball power and fraction of thermal energy versus scaled time in second thermal pulse.

(Text continued from page 331.)

equivalent, but if it is required in calories the result is multiplied by 10^{12}.

7.114 The curves in Fig. 7.111 present some features of special interest. As is to be expected, the thermal power (or rate of emission of radiant energy) of the fireball rises to a maximum, just as does the temperature in the second radiation pulse. However, since the thermal power is roughly proportional to T^4, it increases and decreases much more rapidly than does the temperature. This accounts for the sharp rise to the maximum in the P/P_{max} curve, followed by a somewhat less sharp drop which tapers off as the ball of fire approaches its final stages.

7.115 From the standpoint of protection against skin burns, by taking evasive action, the important quantity is t_{max}, since the rate of emission of thermal radiation from the ball of fire is then a maximum. It is seen from the relationship in § 7.112 that this time increases in proportion to the square root of the energy yield of the explosion. Thus, t_{max} is about 0.1 second for a 10-kiloton explosion, but it is over 3 seconds for a burst with 10 megatons energy yield. At such respective distances where severe burns might be experienced, evasive action would thus be expected to achieve greater relative success foı explosions of high energy yield.

Thermal Energy-Distance Relationship

7.116 The next matter to consider is the variation with distance from the explosion of the total thermal energy (in calories) received per square centimeter of a target material. As seen earlier in this chapter, such information, combined with the data in Tables 7.45, 7.61, and 7.65, permits estimates to be made of the probable ranges for various thermal radiation effects.

7.117 If there is no atmospheric attenuation, the thermal energy, E_{tot}, at a distance D from the explosion, may be regarded as being spread uniformly over the surface of a sphere of area $4\pi D^2$. If attenuation were due only to absorption, this quantity would be multiplied by the factor e^{-kD}, where k is an absorption coefficient averaged over the whole spectrum of wave lengths. Hence, in these circumstances, using the symbol Q to represent the thermal energy received per unit area at a distance D from the explosion, it follows that

$$Q = \frac{E_{tot}}{4\pi D^2} e^{-kD}.$$

Since, according to the results given in § 7.112, E_{tot} is equal to $\frac{1}{3}W \times 10^{12}$ calories, where W is the explosion yield in kilotons, the appropriate expression would be

$$Q \text{ (cal/sq cm)} = \frac{10^{12}We^{-kD}}{12\pi D^2},$$

where the distance D is in centimeters.

7.118 When scattering of the radiation occurs, in addition to absorption, the coefficient k is no longer a constant but is a function of distance, and it is then not convenient to express the attenuation by means of an exponential factor. A more useful formulation which has been developed is represented by

$$Q\text{(cal/sq cm)} = \frac{10^{12}WT}{12\pi D^2}, \qquad (7.118.1)$$

where the transmittance, T, that is, the fraction of the radiation transmitted, is a complex function of the visibility (scattering), absorption, and distance. The variation of T with distance from the explosion is shown by the curve in Fig. 7.118. This curve was actually computed for the case of a visibility of 10 miles and for air having a water vapor concentration, which determines the absorption, of 10 grams per cubic meter. Calculations for other reasonable atmospheric conditions have given results which do not differ very greatly from those in Fig. 7.118, and it appears that the same transmittance curve may be used in all cases without serious error, provided the distances are not greater than half the visibility.

7.119 In order to simplify the use of equation (7.118.1), the values of Q for various distances, D, from the explosion, are plotted for $W=1$ kiloton in Fig. 7.119. The thermal energy received at any distance from an explosion of W kilotons is then obtained upon multiplying the thermal energy for the same distance in Fig. 7.119 by W.

Flash Burn Energy and Total Energy Yield

7.120 Since t_{max} increases with the total energy yield, it is evident that a given quantity of thermal radiation energy will be received in a shorter time from an explosion of low yield than from one of higher yield. Hence, it is to be expected that the thermal energy required to produce flash burns of any given kind will increase with the energy yield of the explosion, as pointed out earlier. On the basis of labora-

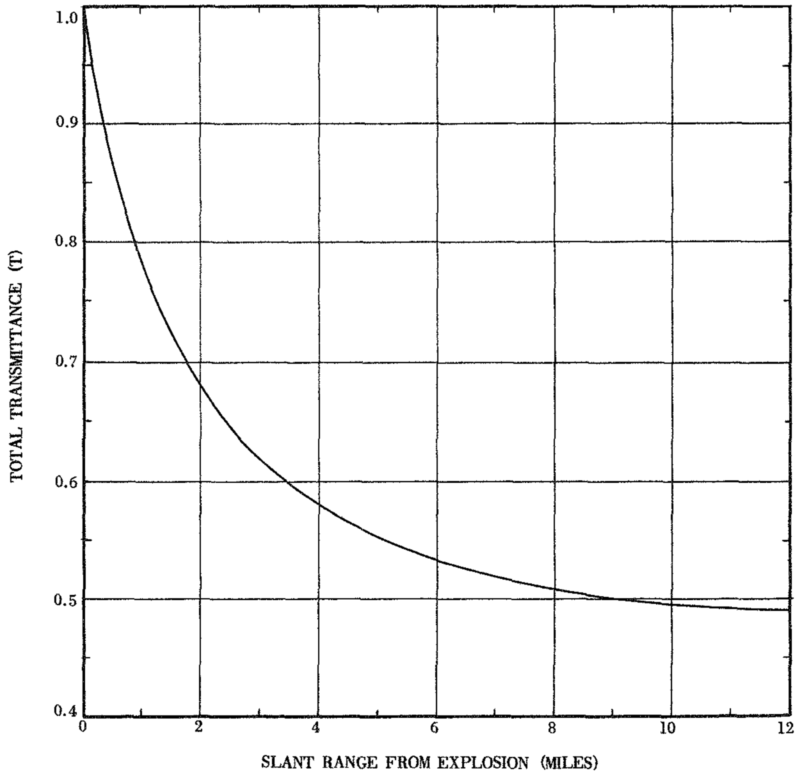

Figure 7.118. Total transmittance for 6000° K black body source (10 mile visibility, 10 gm/cubic meter water vapor concentration).

tory measurements, observations at nuclear tests, and theoretical calculations, estimates have been made of the amounts of thermal energy required to produce moderate first-, second-, and third-degree burns as a function of explosion yield. The results are given in Fig. 7.120.

7.121 It is by combining these data with those derived above for the variation of thermal energy received with distance from an explosion of given yield that the curves in Fig. 7.47 were obtained. Thus, in the example facing Fig. 7.119 it was found that at a distance of 3 miles from a 100-kiloton air burst the thermal energy received is 8 calories per square centimeter. From Fig. 7.120 it is seen that this amount of thermal energy from a 100-kiloton explosion may be expected to produce a third-degree burn.

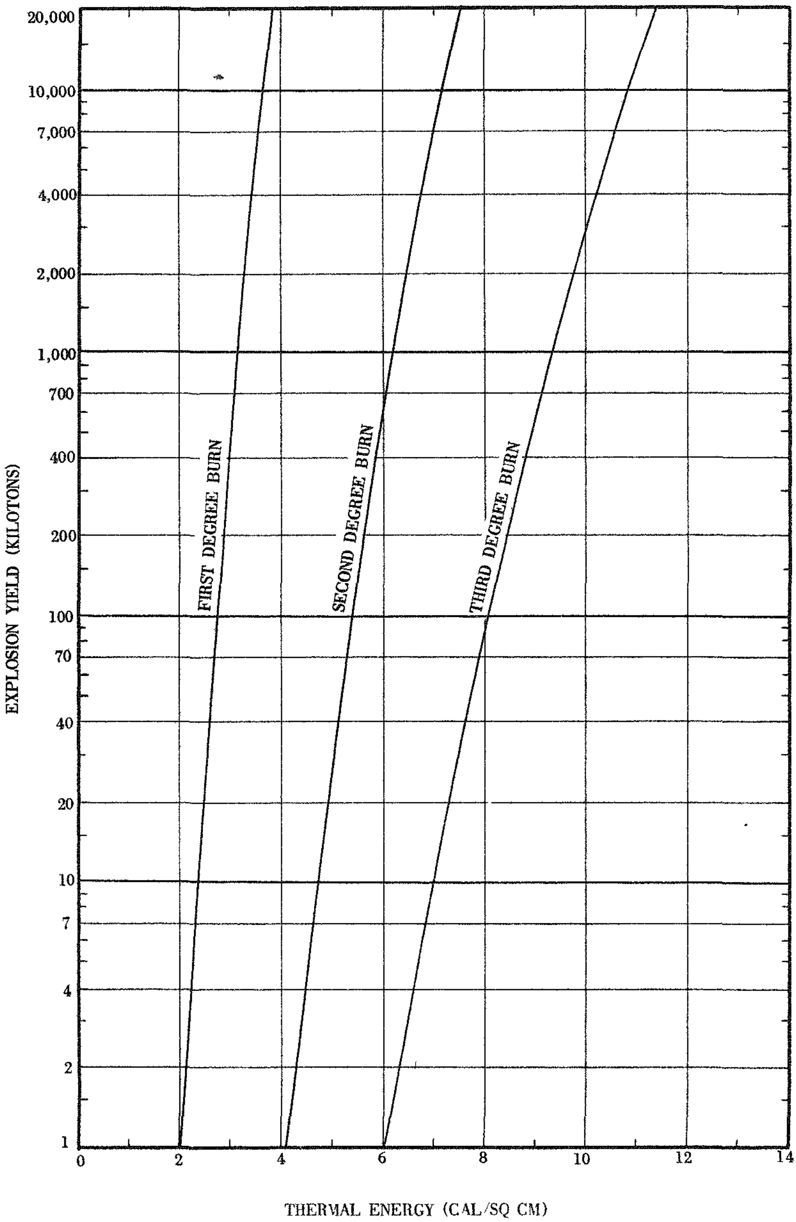

Figure 7.120. Thermal energy required for burns on bare skin.

The plot, which is in two parts for convenience of representation, shows the amount of thermal energy (in calories per square centimeter) received at various distances from a 1 KT air burst for atmospheric visibility in the range of 2 to 50 miles.

Scaling. The thermal energy received at any specified distance from a *W* KT explosion is *W* times the value for the same distance from a 1 KT burst.

Example

Given: A 100 KT air burst and a visibility of 10 miles.

Find: The amount of thermal energy received at a distance of 3 miles from the explosion.

Solution: From Fig. 7.119 the amount of thermal energy received at 3 miles from a 1 KT air burst is 0.08 calorie per square centimeter. Consequently, the thermal energy received at 3 miles from a 100 KT air burst is

$100 \times 0.08 = 8$ calories per square centimeter. *Answer*

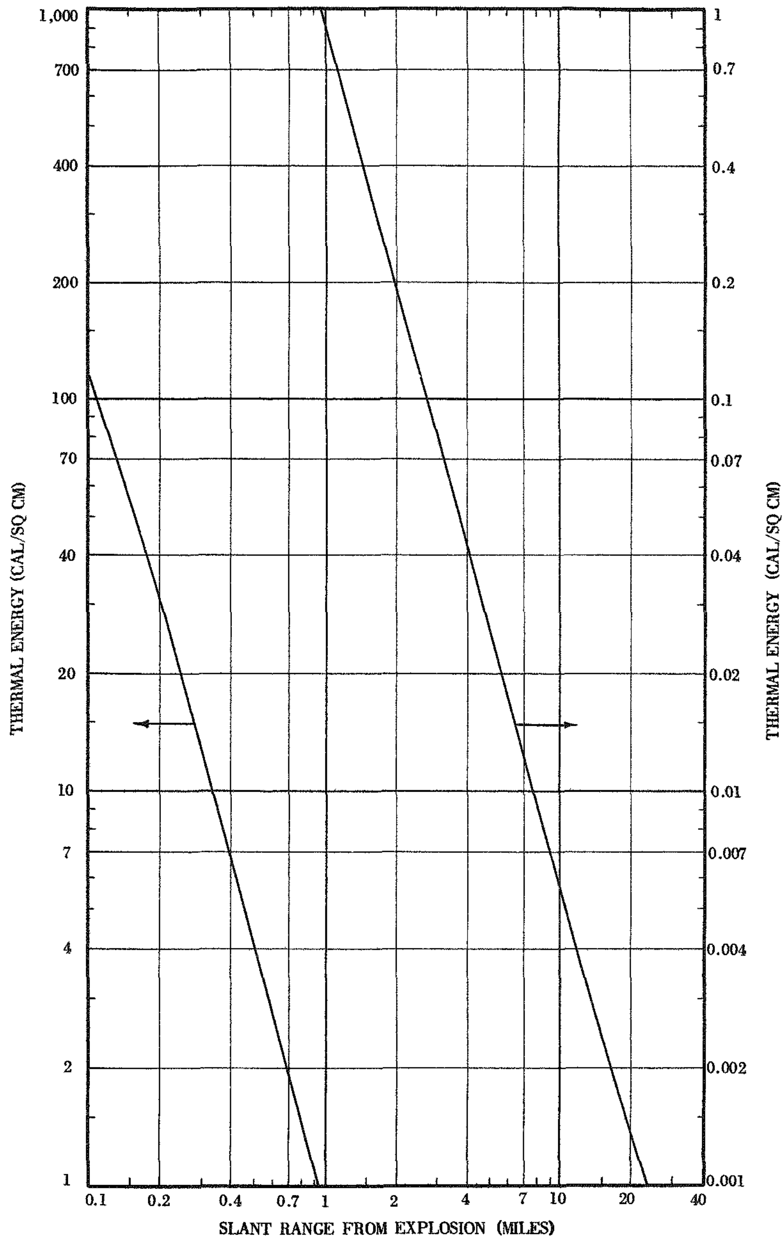

Figure 7.119. Thermal energy received at various slant ranges for a 1-kiloton air burst with visibility of 2 to 50 miles.

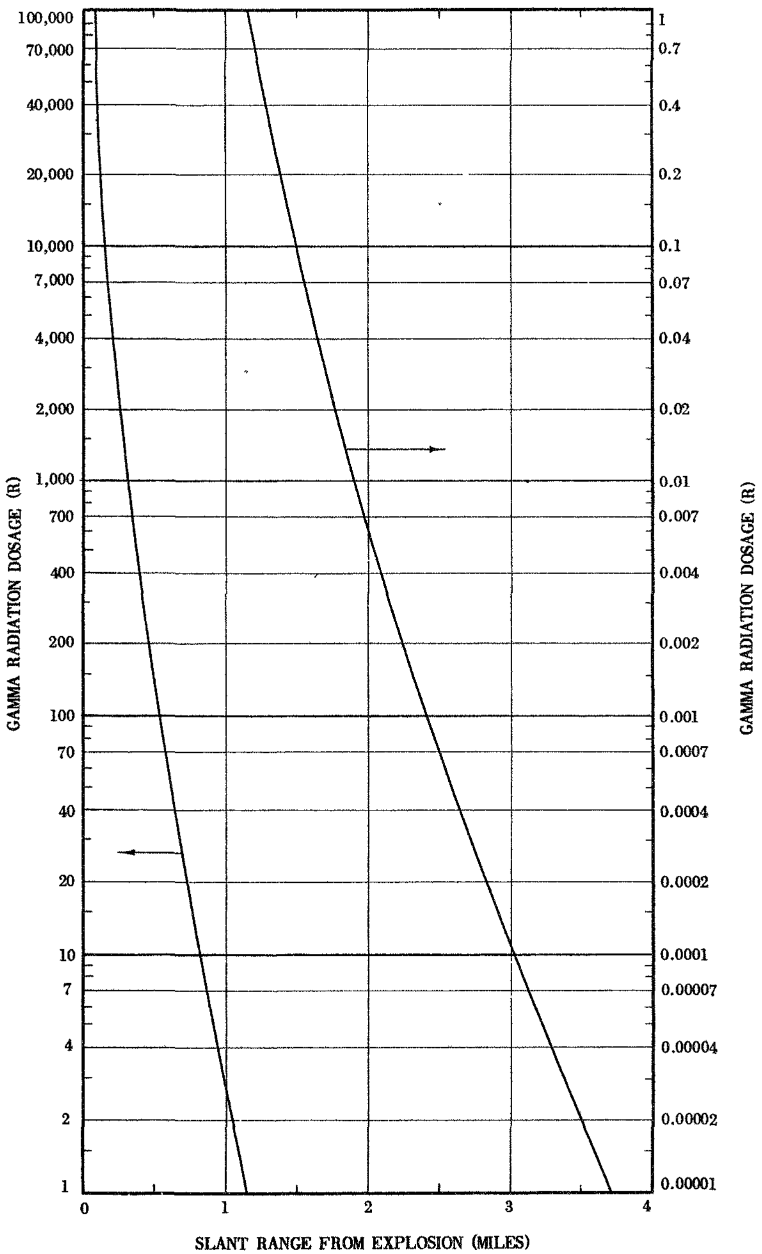

Figure 8.35a. Initial gamma radiation dosage for a 1-kiloton air burst.

is, a fair estimate can be made by assuming that the product of the half-value layer in inches and the density in pounds per cubic foot is about 800.

TABLE 8.44

APPROXIMATE HALF-VALUE LAYER THICKNESSES OF MATERIALS FOR INITIAL GAMMA RADIATION

Material	Density (lb/cu ft)	Half-value thickness (inches)	Product
Steel	490	1. 5	735
Concrete	144	6. 0	864
Earth	100	7. 5	750
Water	62. 4	13	811
Wood	34	23	782

8.46 The attenuation factor of a given shield, that is, the ratio of the dose falling upon the shield to that which would be received behind the shield, can be readily calculated from the number of half-value thicknesses, together with the data in Table 8.44. For example, a 30-inch thick shield of earth will contain $30/7\frac{1}{2}=4.0$ half-value

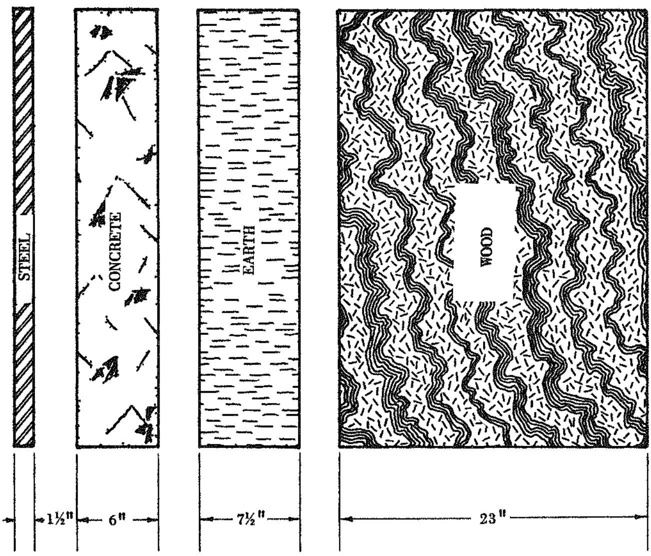

Figure 8.45 Comparison of the half-value layer thicknesses.

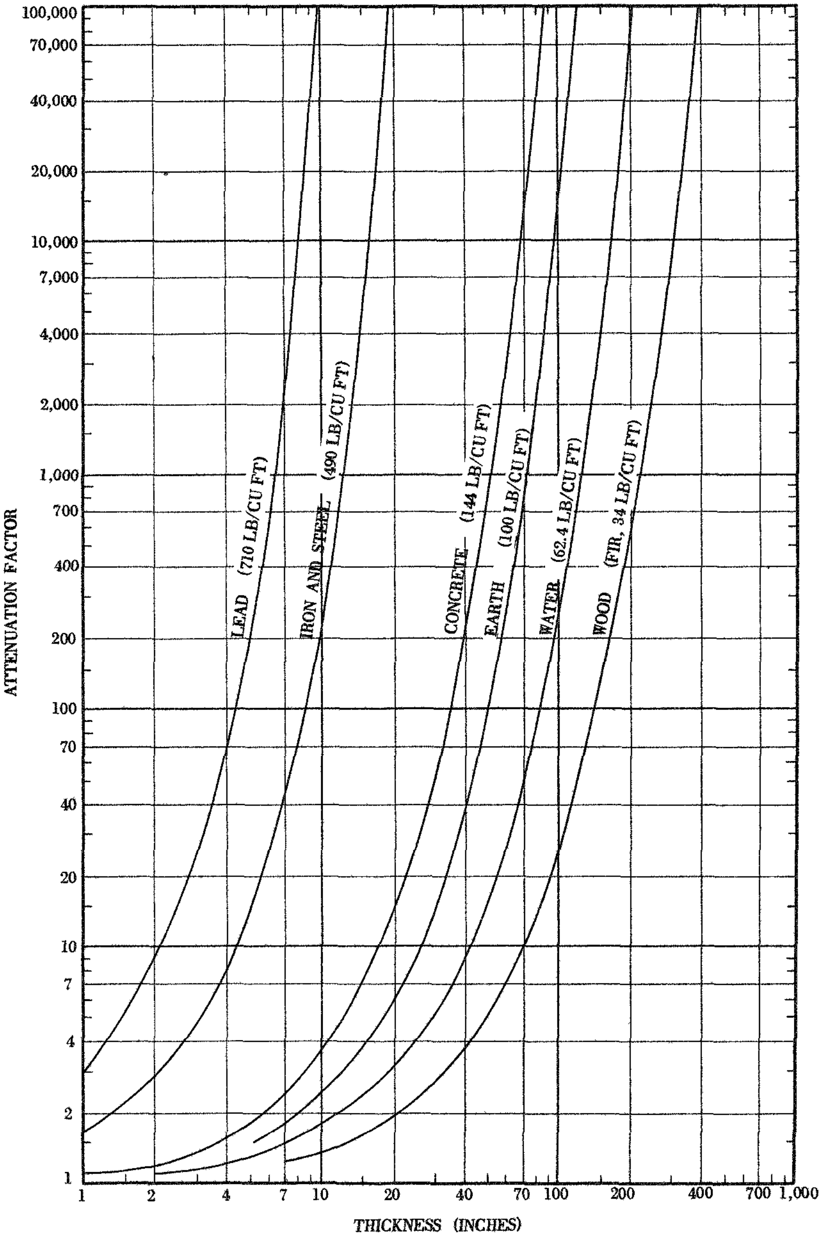

Figure 8.47. Attenuation of initial gamma radiation.

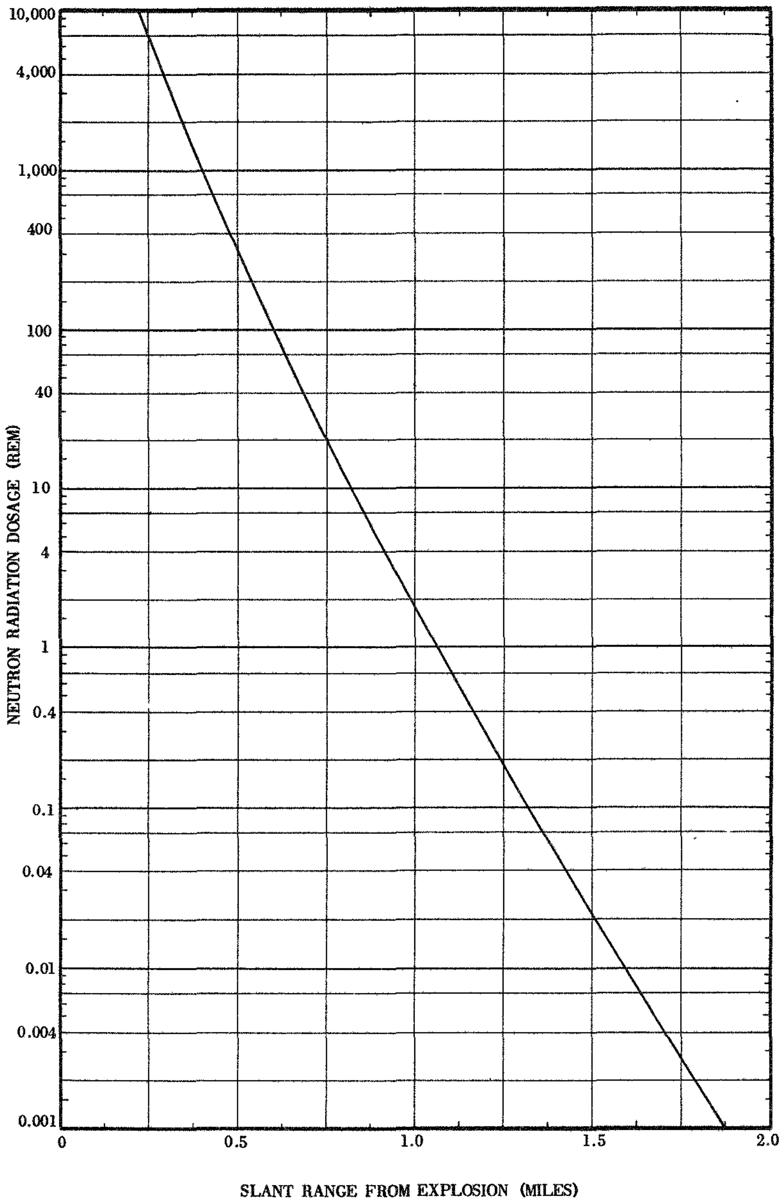

Figure 8.71. Neutron biological dosage for a 1-kiloton air burst.

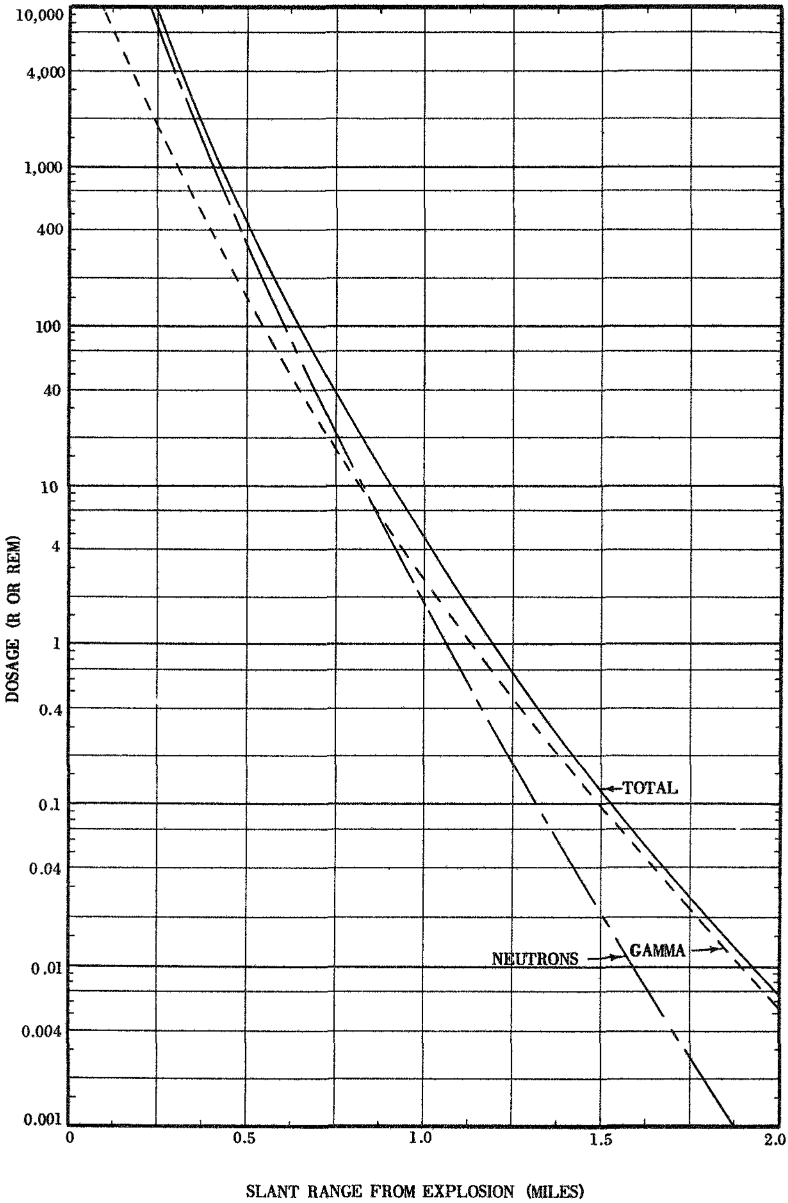

Figure 8.80. Comparison of neutron and initial gamma radiation dosages for a 1-kiloton air burst.

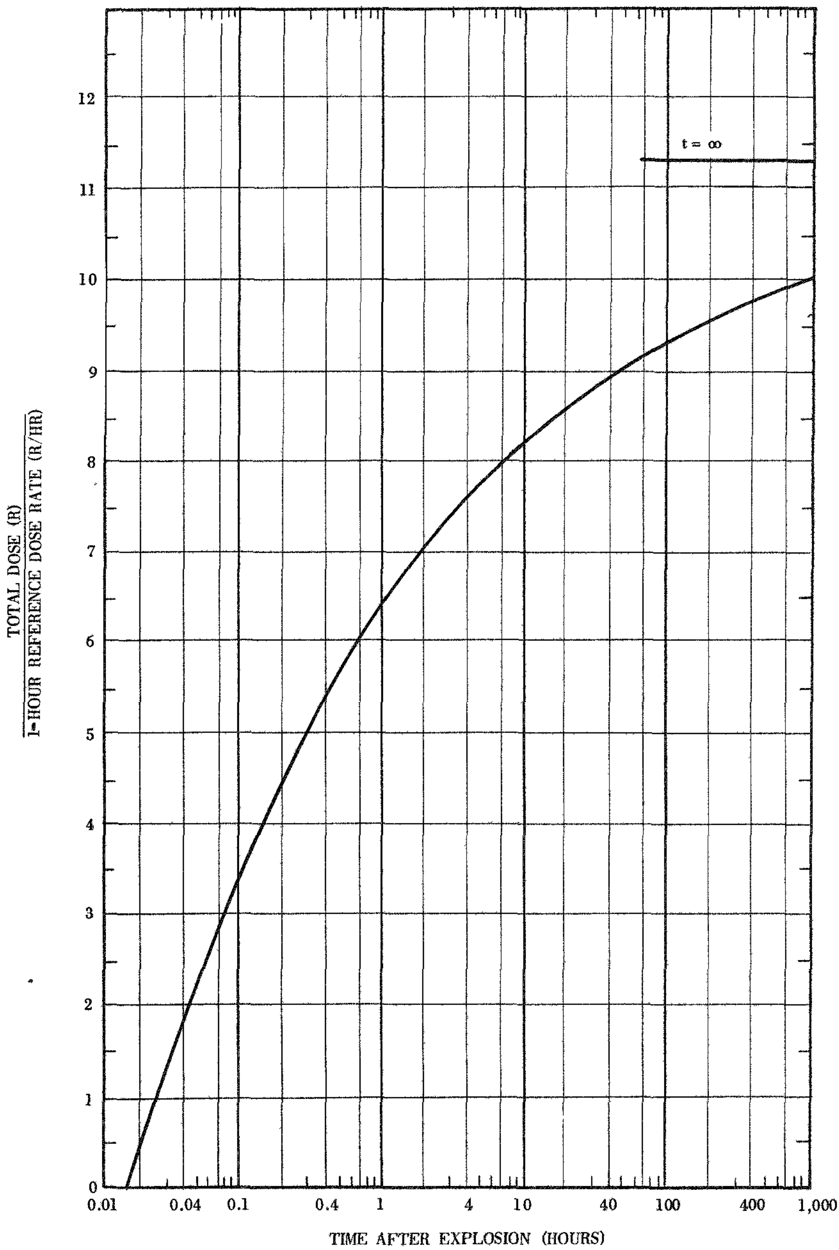

Figure 9.12. Accumulated total dose of residual radiation from fission products from 1 minute after the explosion.

gamma radiation. Except for the earliest stages of decay, however, the gamma rays from fission products have much less energy, on the average, than do those emitted in the first minute after a nuclear explosion.[4] This means that the residual gamma rays are more easily attenuated; that is to say, compared with the initial gamma radiation, a smaller thickness of a given material will produce the same degree of attenuation.

9.35 Bearing in mind the limitations stated in § 8.43, the approximate half-value thicknesses of some common materials for the gamma radiations from fission products are given in Table 9.35. Upon comparing these thicknesses with those in Table 8.44 for the initial gamma radiation, it is seen that the residual radiation is more easily attenuated. The order of effectiveness of different materials is, however, the same in both cases, since it is largely (although not entirely) determined by the density. The figures in the last column of Table 9.35 show that the product of the half-value thickness and the density of the material is roughly the same in all the cases mentioned (§ 8.45).

TABLE 9.35

APPROXIMATE HALF-VALUE LAYER THICKNESSES OF MATERIALS FOR GAMMA RAYS FROM FISSION PRODUCTS

Material	Density (lb/cu ft)	Half-value thickness (inches)	Product
Steel	490	0.7	343
Concrete	144	2.2	317
Earth	100	3.3	330
Water	62.4	4.8	300
Wood	34	8.8	300

9.36 The attenuation factors, as defined in § 8.46, for steel, concrete, soil, and wood, for a range of thicknesses of these materials, are represented graphically in Fig. 9.36, which is analogous to Fig. 8.47 for the initial gamma radiation. It is seen that attenuation of the residual radiation by a factor of 50 requires 15 inches of concrete. This is compared with 29 inches needed to produce the same degree of attenuation of the initial gamma radiation, as given in § 8.47.

[4] The average energy of the gamma rays from fission products, except during the early stages of decay, is about 0.7 Mev per photon. This may be compared with an effective value of roughly 4.5 Mev for the initial gamma radiations (§ 8.92).

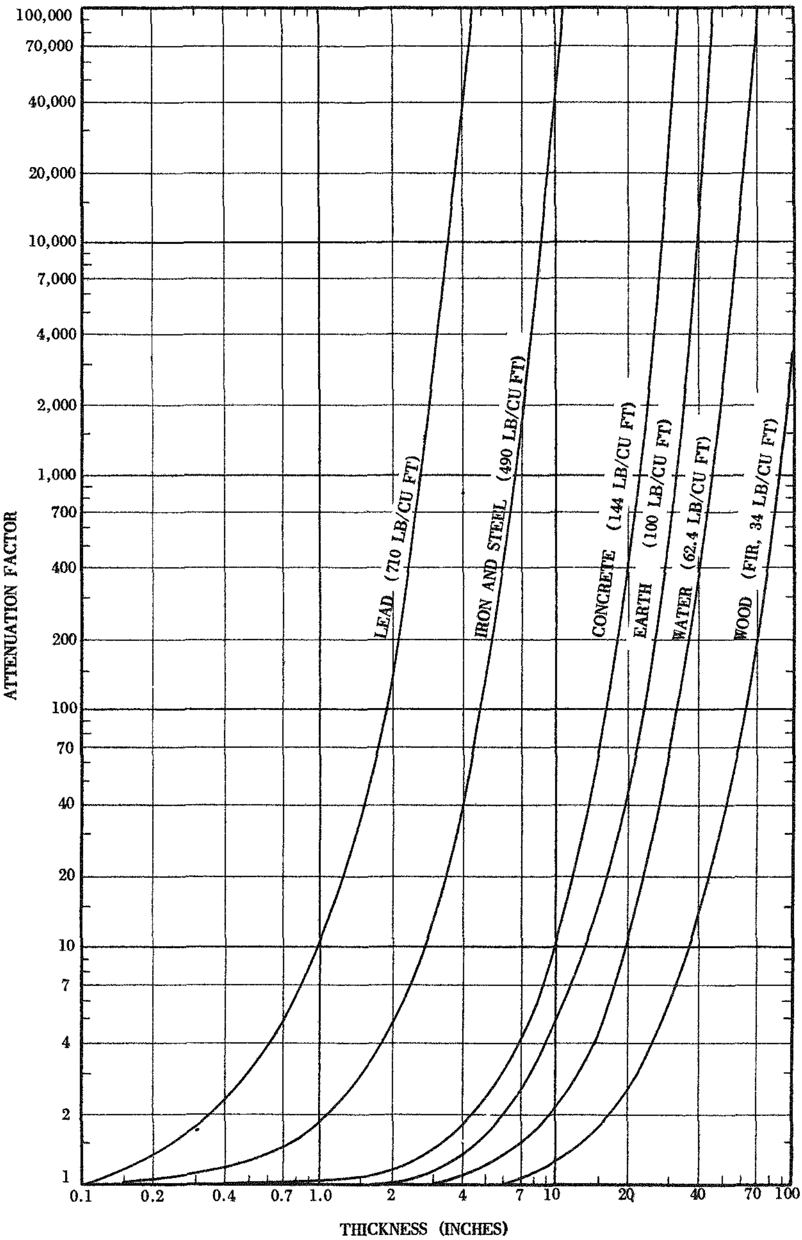

Figure 9.36. Attenuation of fission product radiation.

9.37 From the practical standpoint, it is of interest to record the attenuation factors that might be expected inside various structures. Two factors are responsible for this attenuation. First, there is the effect of distance, because the source of the radiation will be mostly outside, e. g., on the roof or in the street; and second, there is partial absorption of the radiation by the roof and walls. The approximate values given in Table 9.37 have been estimated partly from calculations and partly on the basis of field measurements. It will be noted that in the basement of a frame house the residual gamma radiation is reduced to about one-tenth of its value outside the house. A 3-foot layer of earth attenuates the radiations to one-thousandth (or less) of the intensity it would otherwise have at the same location.

TABLE 9.37

ESTIMATED ATTENUATION FACTORS IN STRUCTURES FOR RESIDUAL GAMMA RADIATION

Type of Structure	Approximate attenuation factor
Frame house:	
First floor	2
Basement	10
Multistory, reinforced concrete:	
Lower floors (away from windows)	10
Basement (surrounded by earth)	*1, 000
Shelter below grade:	
3 feet of earth	*1, 000

*Or more.

ASPECTS OF RADIATION EXPOSURE

Acute and Chronic Exposure

9.38 In considering the injurious effects on the body of gamma radiations from external sources, it is necessary to distinguish between an "acute" (or "one-shot") exposure and a "chronic" exposure. In an acute exposure the whole radiation dose is received in a relatively short interval of time. This is the case, for example, in connection with the initial nuclear radiation considered in the preceding chapter. It is not possible to define an acute dose precisely, but it may be

somewhat arbitrarily taken to be a dose received during a 24-hour period. The delayed radiations from the fission products persist over a longer period of time, however, and the exposure may then be of the chronic type.

9.39 The importance of making a distinction between acute and chronic exposures lies in the fact that, if the dose rate is not too large, the body can achieve partial recovery from some of the consequences of nuclear radiations while still exposed. Thus, apart from certain effects mentioned below, a greater total gamma-radiation dose would be required to produce a certain degree of injury if the dose were spread over a period of several days than if the same dose were received within a minute or so.

9.40 It was stated in § 8.26 that an acute gamma-radiation exposure dose of 450 roentgens, over the whole body, would be expected to prove fatal to about 50 percent of the individuals so exposed. If the same number of roentgens were received over a period of a few weeks, the probability of death would be less. Because of the many factors involved, it is not possible to state, at the present time, the exact degree of recovery that might be expected during the course of chronic radiation exposure. From some effects, e. g., genetic changes, there is apparently no recovery (see § 11.124), but, as far as the more obvious injuries are concerned, all that can be said definitely is that a given radiation dose spread over a period of time, e. g., two weeks or more, is less harmful than an acute dose of the same number of roentgens (or rems) received in 24 hours.

NATURAL BACKGROUND RADIATION

9.41 In connection with the matter of chronic radiation doses, it may be noted that human life has become adapted to a certain amount of radiation, received continuously over a long period of time. This statement is based on the fact that all living creatures are always exposed to radiations from various natural sources, both inside and outside the body. The chief internal source is the radioisotope potassium-40, which is a normal constituent of the element potassium as it exists in nature. Carbon-14 in the body is also radioactive, but it is only a minor source of internal radiation. There is also some potassium-40, as well as radioactive uranium, thorium, and radium, in varying amounts, present in soil and rocks. Finally, an important source of nuclear radiation in nature is the so-called "cosmic rays," originating in outer space. The radiation dose received from those

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rays increases with altitude; at 15,000 feet, it is more than five times as large as at sea level.

9.42 An estimate of the total radiation dose, due to purely natural sources, received per annum by human beings, over the whole body, is given in Table 9.42. It is assumed that the underlying rock is granite, and data are given for sea level and an elevation of 5,000 feet. In some locations the background radiation dose from soil and rocks is less than from granite, but it appears that, in most parts of the United States, the natural radiation exposure dose is about 0.14 to 0.16 roentgen per year.

TABLE 9.42

ESTIMATED DOSE PER ANNUM FROM NATURAL BACKGROUND RADIATION

Radiation source	Roentgens per year	
	Sea level	5,000 feet altitude
Potassium in body	0. 020	0. 020
Thorium, uranium, and radium in granite	0. 055	0. 055
Potassium in granite	0. 035	0. 035
Cosmic rays	0. 035	0. 050
Total	0. 145	0. 16

9.43 It follows, therefore, that during the average lifetime every human being receives a total of 10 to 12 roentgens of nuclear radiation over the whole body from natural sources. In addition, there may be localized exposures associated with dental and chest X-rays, and similar treatments, and even from the luminous dials of wrist watches and instruments. The exposure to radiation from natural sources has undoubtedly continued during the whole period of man's existence.

MAXIMUM PERMISSIBLE RADIATION EXPOSURE

9.44 It is evident that human beings have been (and are being) continually exposed to nuclear radiations, from sources both inside and outside the body. As a result, a steady (or equilibrium) biologi-

cal state has been attained. This fact suggests that, apart from genetic effects, there is a certain chronic radiation dose over which the body has partial power of recovery. As to what this chronic dose is, there is no definite knowledge. In any event, it probably varies from one individual to another.

9.45 In spite of the uncertainty concerning what might be called the "permissible" dose, some general conclusions have been reached on the basis of information obtained from radiologists and X-ray technicians, from observations on biological damage caused by radium, and from animal experiments. These conclusions may be revised from time to time as further data on the effects of various nuclear radiations on living organisms become available.

9.46 With the development of peaceful, as well as military, applications of nuclear energy, many people are now exposed to additional amounts of nuclear radiations during working hours, over and above that of the background. In order to safeguard the health of occupationally exposed adults, a "maximum permissible exposure" of 0.3 roentgen per week has been established in the United States. It is considered at present, therefore, that such persons, occupied in atomic industries, may be exposed to 0.3 roentgen per week, i. e., 15 roentgens per year, of nuclear radiation over the whole body for a period of many years without undue risk.[5]

9.47 The purpose of the foregoing discussion is to point out that exposure to nuclear radiation is by no means a new experience for the human race. Further, it appears to be established that the body has the power of partial recovery from certain effects due to moderate chronic doses of radiation. The maximum permissible chronic dose recommended for workers in nuclear energy projects is felt to include a factor of safety. There is evidence, in fact, of individuals who have received much larger doses of nuclear radiation, and have no discernible evidence of permanent damage. Nevertheless, it must not be forgotten that exposure to sufficiently large doses of radiation, either chronic or acute, can cause serious injury and even death (see Chapter XI).

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[5] Recommendations of the National Committee on Radiation Protection and Measurement appearing in a paper on "Maximum Permissible Radiation Exposures to Man" *Radiology, 68,* 260 (1957) state that "The maximum permissible accumulated dose, in rems, at any age, is equal to 5 times the number of years beyond age 18, provided no annual increment exceed 15 rems", and that "The maximum permissible dose to the gonads for the population of the United States as a whole from all sources of radiation, including medical and other man-made sources, and background, shall not exceed 14 million rems per million of population over the period from conception up to age 30, and one-third that amount in each decade thereafter."

RADIOACTIVE CONTAMINATION IN NUCLEAR EXPLOSIONS

CONTAMINATION IN AN AIR BURST

9.48 There are two main ways in which the earth's surface can become contaminated with radioactive material as a result of a nuclear explosion. One is by the induced activity following the capture of neutrons by various elements present in the soil (or sea), and the other is by the fallout, that is, by the subsidence of radioactive particles from the column and cloud formed in the explosion (§ 2.21). Both the relative and actual importance of these two sources of contamination depend very greatly upon the location of the point of burst with regard to the surface of the earth, and also upon the energy yield of the explosion. Other factors which may affect the contamination are the nature of the terrain and meteorological conditions.

9.49 In an air burst the radioactive bomb residues, consisting largely of the fission products, condense into very small solid particles. In this finely divided state a portion of the radioactive particles enter the stratosphere and will remain suspended for many years, even circling the earth several times, before descending to the surface. During this period they undergo decay and loss of activity. Hence, when the particles do reach the earth's surface, they will be widely dispersed and their radioactivity will be very greatly reduced. In fact the external radiation produced by the fallout from a weapon with a fission yield in the megaton range would be extremely small in comparison with the natural background radiation (see, however, Chapter X).

9.50 Under certain meteorological conditions, e. g., abnormal winds or a rainfall situation, there might be appreciable fallout, probably of a localized character. For example, in a moist atmosphere the fine particles of bomb residue could attach themselves to water droplets which might subsequently fall as radioactive rain. Such was apparently the case in the moderately low air burst over Bikini Lagoon (Test ABLE) in 1946, as stated in § 2.98. The extent of the activity was, however, small, since most of the fission products were probably above the rain clouds at the time.

9.51 A special case of interest is that of a warm front rainfall situation, such as frequently occurs in temperate latitudes. The rain-bearing clouds may have a thickness of 20,000 feet and can extend over many hundreds of square miles. The rain is usually gentle, but continues to fall steadily for some time. If the situation existed at the time of the explosion, the radioactive particles formed in the air burst might ascend into the rain-bearing clouds. In a short time, the atomic cloud, if it did not rise above the rain-bearing cloud, would become so mixed with the latter as to become an integral part of the rain-

producing system. The radioactive material might then be expected to deposit with the rain over a large area, in a surface pattern dependent upon the winds at the cloud level.

9.52 An air burst of a small yield weapon would not be accompanied by serious local fallout except possibly in unusual circumstances, as is borne out by the fact that there were no casualties in the nuclear bombings of Japan that could be attributed to residual radiation. At Nagasaki, about 0.02 percent of the fission products was deposited on the surface within a radius of 2,000 feet (0.4 mile) of ground zero. However, at no time did this represent a significant radiation hazard. Observations made at tests indicate that the local fallout from air bursts is also small for large yield weapons.

9.53 An important source of contamination due to residual nuclear radiation from an air burst can be the activity induced by neutrons captured by elements, notably sodium and manganese, on the earth's surface (§ 9.21, *et seq.*) The amount of the contamination, which will be appreciable only in a limited area about ground zero, will depend upon the height of burst, the energy yield, and the time elapsed since the explosion. At Hiroshima and Nagasaki, for example, the induced radioactivity on the surface was believed to be negligible. In the ABLE test at Bikini, however, where the height of burst was less than in the Japanese explosions, an appreciable amount of radioactive sodium-24 was formed in the water. The gamma rays from this isotope gave a dose rate of about 1 roentgen per hour just above the surface of the lagoon at 2 hours after the burst.

9.54 A low air burst of a nuclear weapon of high energy could result in extensive contamination due to induced activity in the vicinity of ground zero. In this region, destruction by blast and fire, except for strong underground structures, would be virtually complete.

Contamination in a Surface Burst

9.55 In an air burst, the neutron-induced activity may be significant, but the local fallout, soon after the explosion, will generally be unimportant. The fission products will, however, contribute to the activity of the gradual fallout extending over large areas. With a surface (or subsurface) burst, on the other hand, the local fallout will assume major significance. Although there will undoubtedly be a considerable amount of induced radioactivity near ground zero, the activity of the fission product fallout will be so much greater in a surface burst that the induced activity can be neglected in comparison.

Consequently, the subsequent discussion of the residual radiation following a surface burst will deal mainly with the (local) fallout of fission products.

9.56 The fraction of the total radioactivity of the bomb residues that appears in the fallout depends upon the extent to which the ball of fire touches the surface. Thus, the proportion of the available activity increases as the height of burst decreases and more of the fireball comes into contact with the earth. In the case of a contact burst, i. e., one in which the bomb is actually on the surface when it explodes, some 50 percent of the total residual radioactivity will be deposited on the ground within a few hundred miles of the explosion. The remainder of the activity will stay suspended for a long time and will eventually reach the earth many hundreds or thousands of miles away, as in the case of an air burst (§ 9.49).

9.57 In a surface burst, large amounts of earth, dust, and debris are taken up into the fireball in its early stages. Here they are fused or are vaporized and become intimately mixed with the fission products and other bomb residues, as described in § 2.21. As a result, there is formed upon cooling a tremendous number of small particles contaminated to some distance below their surfaces with radioactive matter. In addition, there are considerable quantities of pieces and particles, covering a range of sizes from large lumps to fine dust, to the surfaces of which fission products are more or less firmly attached.

9.58 The larger (heavier) pieces, which will include a great deal of contaminated material scoured and thrown out of the crater (§ 5.4), will not be carrried up into the mushroom cloud, but will descend from the column. Provided the wind is not excessive, this large particulate material, as it falls, will form a roughly circular pattern around ground zero. Actually, the center of this circular pattern, called the "ground zero circle," will usually be displaced somewhat from ground zero by the wind.

9.59 Most of the contaminated material referred to above, forming the ground zero circle, descends within a short time, not more than an hour or so. The smaller particles present in the atomic column are, however, carried upward to a height of several miles (§ 2.16) and may spread out some distance in the mushroom cloud before they begin to descend. The time taken to reach the earth and the horizontal distance traveled will depend upon the height reached before they begin to fall, the size of the particles, and upon the wind pattern in the upper atmosphere. The smallest (and lightest) particles, like those formed in an air burst, will enter the stratosphere and remain suspended for long periods and may travel many thousands of miles

before descending (§ 9.49). Most of the larger particulate matter, however, will probably reach the earth as local fallout within a few hundred miles from ground zero.

9.60 As a general rule, it is to be expected that, except for the very smallest particles which descend over a wide area, the fallout of particles of moderate and small size will form, in the course of time, a kind of elongated (or cigar-shaped) pattern of contamination. The shape and dimensions will be determined by the wind velocities and directions at all altitudes between the ground and the atomic cloud. For simplicity of representation, the actual complex wind pattern may be replaced by an approximately equivalent "effective wind." The direction and velocity of this wind are intended to represent weighted averages over the whole wind system to which the particles of the fallout are subjected as they descend to earth as local fallout from the atomic cloud (see § 9.140).

9.61 In Fig. 9.61 an attempt is made to generalize the pattern of contamination due to the residual nuclear radioactivity from a nuclear

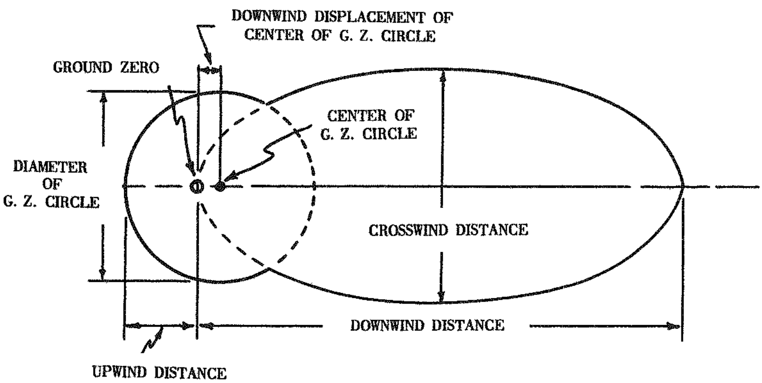

Figure 9.61. Generalized fallout pattern.

explosion near the earth's surface. The figure shows the ground zero (GZ) circle, corresponding to a particular dose rate (or total dose) of nuclear radiation at a specified time. Its center is somewhat displaced from actual ground zero by the wind in the vicinity of the explosion. The direction of this wind is assumed to be the same as that of the effective wind for the fallout, but this will not necessarily always be the case. The complete ground zero contamination pattern will consist of a series of circles, each representing a dose-rate (or dose) contour, for a specified dose-rate (or dose) of residual radiation.

9.62 The ellipse, with its long axis in the direction of the effective wind, is a simplified dose-rate (or dose) contour for the fallout. Here again, the complete fallout contamination pattern can be represented by a series of such ellipses. At a particular time after the explosion, the dose rate (or dose) is apt to be less, the greater the distance from ground zero, because the amount of fallout per unit area is also likely to be less. In some cases (see Fig. 9.63b) the contours represent the total dose received from fallout up to a certain time. An additional factor then contributes to the decrease with increasing distance from the explosion. The later times of arrival of the fallout at these greater distances mean that the fission products have decayed to some extent while the particles were still suspended in the air. At the time the fallout reaches the ground, the activity of a certain mass at a considerable distance from the point of detonation will thus be less than that of an equal mass which has descended closer to ground zero.

9.63 Some indication of the manner in which the fallout pattern develops over a large area during a period of several hours following a nuclear surface burst of high yield may be illustrated by the diagrams in Figs. 9.63a and b. The effective wind velocity was taken as 15 miles per hour. Fig. 9.63a shows a number of contours for certain (arbitrary) round-number values of the dose rate, as would actually be observed on the ground, at 1, 6, and 18 hours, respectively, after the explosion. A series of total (or accumulated) dose contours for the same times are given in Fig. 9.63b. It will be understood, of course, that the various dose rates and doses change gradually from one contour line to the next. Similarly, the last contour line shown does not represent the limit of the contamination, since the dose rate (and dose) will fall off steadily over a greater distance.

9.64 Consider, first, a location 32 miles downwind from ground zero. At 1 hour after the detonation, the observed dose rate is seen to be about 30 roentgens per hour; at 6 hours the dose rate, which lies between the contours for 1,000 and 300 roentgens per hour, has increased to about 800 roentgens per hour; but at 18 hours it is down to roughly 200 roentgens per hour. The increase in dose rate from 1 to 6 hours means that at the specified location the fallout was not complete at 1 hour after the detonation. The decrease from 6 to 18 hours is then due to the natural decay of the fission products. Turning to Fig. 9.63b, it is seen that the total radiation dose received at the given location by 1 hour after the explosion is quite small, because the fallout has only just started to arrive. By 6 hours, the total dose has reached over 3,000 roentgens (probably around 4,000) and

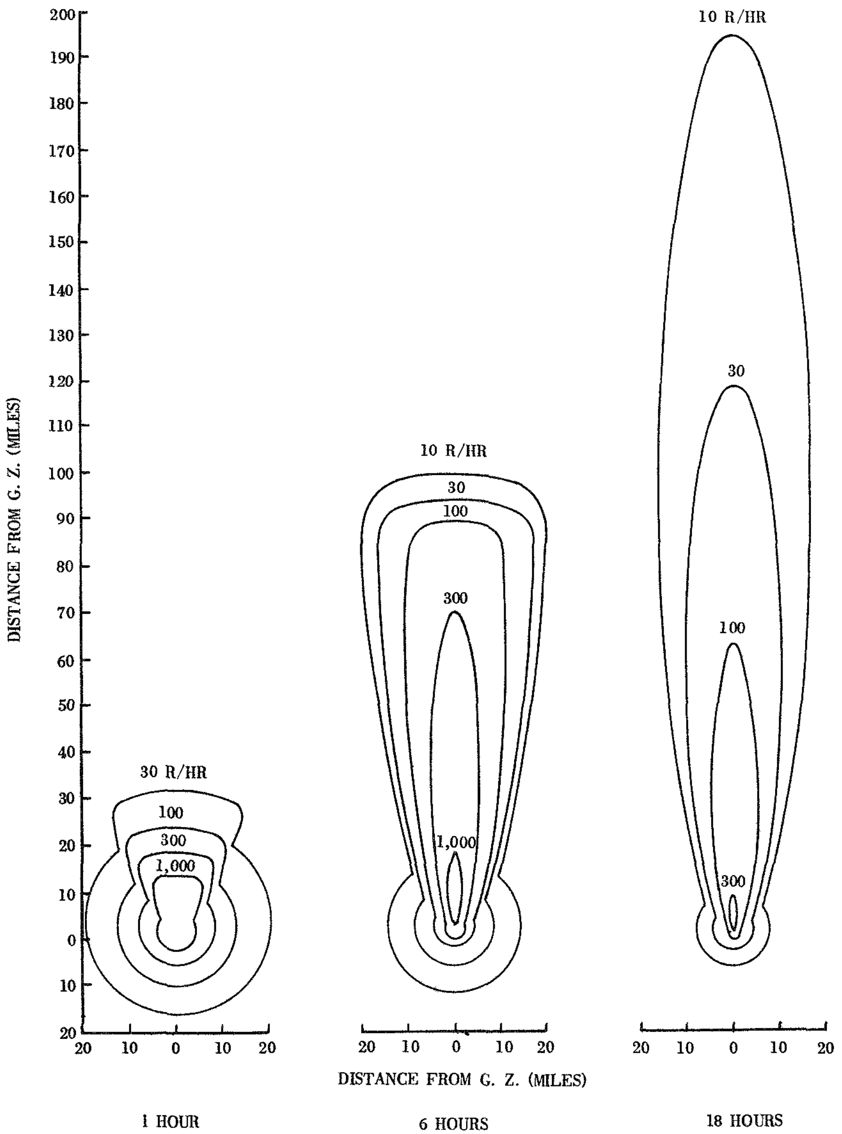

Figure 9.63a. Dose rate contours from fallout at 1, 6, and 18 hours after a surface burst with fission yield in the megaton range (15 mph effective wind).

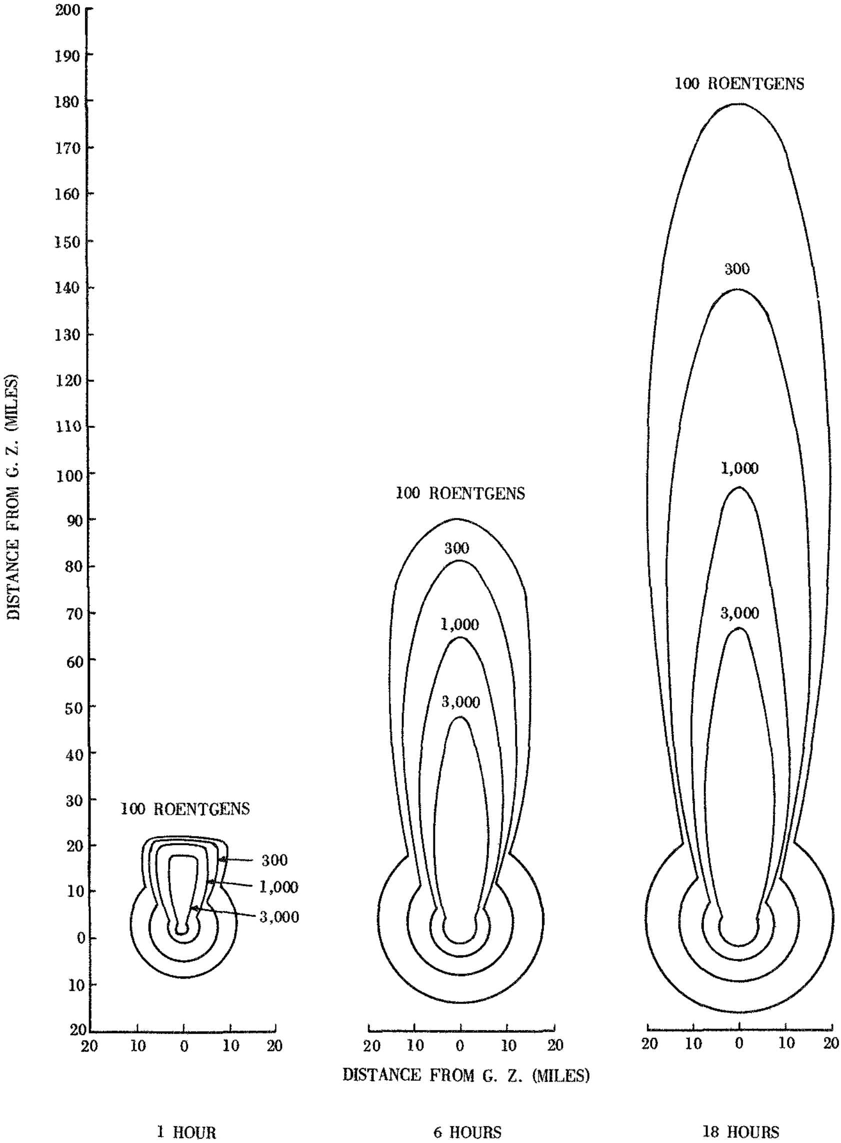

Figure 9.63b. Total (accumulated) dose contours from fallout at 1, 6, and 18 hours after a surface burst with fission yield in the megaton range (15 mph effective wind).

by 18 hours a total dose of some 5,000 roentgens will have been accumulated. Subsequently, the total dose will continue to increase, toward the infinity value, but at a slower rate (§ 9.14).

9.65 Next, consider a point 100 miles downwind from ground zero. At 1 hour after the explosion the dose rate, as indicated in Fig. 9.63a, is very small, probably zero, since the fallout will not have reached the specified location. At 6 hours, the dose rate is 10 roentgens per hour and at 18 hours about 50 roentgens per hour. The fallout commences at somewhat less than 6 hours after the detonation and it is essentially complete at 18 hours, although this cannot be determined directly from the contours given. The total accumulated dose, from Fig. 9.63b, is seen to be zero at 1 hour after the explosion, about 30 roentgens at 6 hours, and nearly 1,000 roentgens at 18 hours. The total (infinity) dose will not be as great as at locations closer to ground zero because the quantity of fission products reaching the ground decreases at increasing distances from the explosion.

9.66 In general, therefore, at any given location, at a distance from a surface burst, some time will elapse until the fallout arrives. This time will depend on the distance from ground zero, the time taken for the particles to descend to earth, and the effective wind velocity. When the fallout first arrives, the exposure dose rate is small, but it increases steadily as more and more fallout descends. In a few hours the fallout will be essentially (although not absolutely) complete, and then the radioactive decay of the fission products will be accompanied by a steady decrease in the dose rate. Until the fallout commences, the total dose will, of course, be zero, but after its arrival the total (accumulated) radiation dose will increase continuously, at first rapidly and then somewhat more slowly, over a long period of time, extending for many months and even years (see Table 9.90).

LOW YIELD EXPLOSIONS

9.67 The basic fallout phenomena associated with a surface burst of low fission yield are essentially the same as those for a high fission yield. Such differences as may exist are ones of degree rather than of kind. The proportionately larger quantity of fission products resulting from a high-energy fission explosion will mean that a larger area will be contaminated to a serious extent than would be the case if the fission yield were low. However, in order to provide a more complete representation of the fallout pattern for a range of fission energies, the results will be given here for a surface burst in the kiloton range and in a later section for one in the megaton range.

9.68 In the program of nuclear test explosions in Nevada, the contamination in the vicinity of the burst has been given detailed study. The majority of these tests produced contamination patterns of the general form shown in Fig. 9.61. Hence, idealized contours of the same type are useful to indicate average, representative values for planning purposes. The contour dimensions for various 1-hour (reference) dose rates from the fallout from a 20-kiloton surface explosion, assuming a 15-mile per hour effective wind, are recorded in Table 9.68. These reference values were calculated from the dose-rate measurements made after fallout was complete, as indicated in § 9.9.

TABLE 9.68

APPROXIMATE RESIDUAL RADIATION 1-HOUR (REFERENCE) DOSE-RATE CONTOURS ON GROUND FOR 20-KILOTON SURFACE BURST

Dose rate (r/hr)	Radius of GZ circle (miles)	Displacement of center of GZ circle (miles)	Downwind distance (miles)	Crosswind distance (miles)
3,000	0. 10	0. 08	1. 0	0. 3
1,000	0. 22	0. 14	2. 3	0. 7
300	0. 41	0. 22	5. 3	1. 2
100	0. 66	0. 28	11. 5	1. 8
30	0. 95	0. 36	22	2. 8
10	1. 4	0. 42	50	5. 1

9.69 It is apparent that the dose rate close to ground zero, especially in the crater region, is very high, so that the area would be uninhabitable because of the radiation hazard. However, this area would be uninhabitable, in any event, because of the complete destruction due to blast and shock, and cratering of the ground.

9.70 In addition to the contamination in the vicinity of ground zero, which is equivalent to the ground zero circle representation in Fig. 9.61, regions of somewhat higher radioactivity than the surroundings, called "hot spots," have been detected on the surface several miles from the explosion center, both at Alamogordo and at the Nevada Test Site. This fallout of fission products is probably due to a special combination of meteorological, atmospheric, and ground conditions leading to increased deposition in a particular region.

High Fission-Yield Explosions

9.71 The contour dimensions for a number of hypothetical (reference) 1-hour dose rates, relating to a 1-megaton fission yield surface burst, are given in Table 9.71, based on an effective wind velocity of 15 miles per hour. The data are obtained, as before, by using the fission product decay curve (Fig. 9.8), or an equivalent mathematical expression, to determine what the dose rate would have been at 1 hour after the explosion, if the fallout at each location had been complete at that time. The upwind extent of any particular dose rate contour given in the table is obtained by subtracting the ground zero (GZ) circle displacement from the ground zero circle radius. For example, the 10 roentgens per hour reference contour extends $11.0-1.65=9.35$ miles upwind.

Table 9.71

APPROXIMATE RESIDUAL RADIATION 1-HOUR (REFERENCE) DOSE-RATE CONTOURS ON GROUND FOR 1-MEGATON SURFACE BURST

Dose rate (r/hr)	Radius of GZ circle (miles)	Displacement of center of GZ circle (miles)	Downwind distance (miles)	Crosswind distance (miles)
3,000	0. 43	0. 60	22	3. 1
1,000	1. 4	0. 80	40	6. 8
300	2. 8	1. 02	70	11. 8
100	4. 7	1. 24	114	16. 7
30	7. 5	1. 46	183	22. 8
10	11. 0	1. 65	317	34. 1

9.72 A more complete (idealized) representation of the contour pattern of the 1-hour (reference) dose rates, for the conditions stated above, is given in Fig. 9.72. Because of the lack of symmetry in the terrain and the effects of winds, the elliptical fallout contours for the residual radiation will not look exactly like those in Fig. 9.72. However, for representation purposes the contours are idealized in accordance with the form shown in Fig. 9.61.

9.73 It is of the utmost importance that the significance of the contours in Fig. 9.72 should not be misunderstood. The fact that the 1-hour (reference) dose rates extend to great distances from ground zero must not be taken to imply that such dose rates exist at 1 hour

(Text continued on page 420)

The figure shows the contours for various values of the 1-hour reference dose rate for the surface detonation of a weapon with a fission energy yield of 1 MT. The effective wind velocity is 15 miles per hour.

Scaling. For fission yields other than 1 MT, use may be made of the following approximate scaling law:

$$R = R_0 \times W^{1/3} \text{ at } d = d_0 \times W^{1/3},$$

where,

R_0 is the 1-hour (reference) dose rate for 1 MT at a distance d_0, and

R is the 1-hour (reference) dose rate for W MT at a distance d.

Example

Given: A weapon of 10 MT fission yield is exploded at the surface.

Find: The value of the dose rate from fallout at a location 215 miles downwind from ground zero at the time of arrival of the fallout at that point, assuming an effective wind of 15 miles per hour.

Solution: Since W is 10, the value of $W^{1/3}$ is $10^{1/3} = 2.15$. The distance d is 215 miles, so that $d_0 = d/W^{1/3} = 215/2.15 = 100$ miles. From Fig. 9.72, it is seen that for a 1 MT surface burst, the value of R_0 at a distance of 100 miles downwind from ground zero, is roughly 150 roentgens per hour. Hence the 1-hour reference dose rate at 215 miles downwind from the 10 MT explosion is given by

$$150 \times 2.15 = 322 \text{ roentgens per hour.}$$

The time of arrival of the fallout at this point is approximately $215/15 = 14.3$ hours after the burst. From Fig. 9.8, the decay factor for 14.3 hours is 0.04. The required dose rate at a point 215 miles downwind from ground zero of a 10 MT surface burst at the time of arrival of the fallout is therefore

$$0.04 \times 322 = 12.9 \text{ roentgens per hour.} \quad \textit{Answer}$$

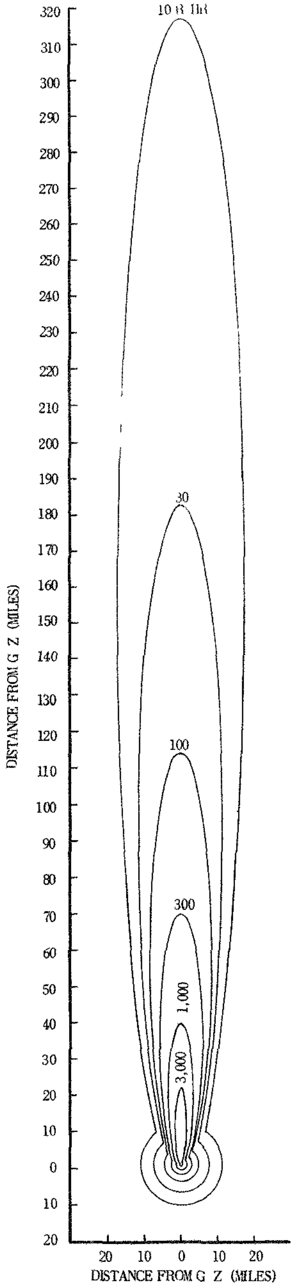

Figure 9.72. Idealized 1-hour reference dose rate contours for fallout after a 1-megaton surface burst (15 mph effective wind).

(Text continued from page 417)

after the explosion. In actual fact, of course, very little of the area shown will have received any fallout at this time. In most regions, as explained in § 9.64, *et seq.*, several hours will elapse before the fallout arrives. The hypothetical 1-hour (reference) dose rate is, nevertheless, very useful for calculations, as shown in the example facing Fig. 9.72.

SCALING

9.74 The residual radiation contours near ground zero for a surface explosion of any specified energy yield can be derived from Tables 9.68 and 9.71 or Fig. 9.72 by the use of approximate scaling laws. For simplicity, it will be assumed that the effective wind is the same in all instances. If the 1-hour (reference) dose rate is R roentgens per hour at a distance d from ground zero for a surface explosion of W megatons fission yield, then according to the approximate scaling law,

$$R=R_0\times W^{1/3} \text{ at a distance } d=d_0\times W^{1/3},$$

where R_0 is the 1-hour (reference) dose rate at a distance d_0 from ground zero in a surface explosion of 1 megaton fission yield. Instead of d (and d_0) representing a distance from ground zero, the same scaling rule will apply to any of the contour dimensions, e. g., radius and displacement of ground zero circles, and downwind and crosswind distances.

9.75 In other words, the contours for a fission yield of W megatons can be obtained by multiplying the data in Table 9.71, including distances and dose rates, by the factor $W^{1/3}$. This simple cube root scaling law has been found to give reasonably good results for fission energy yields between about 0.1 megaton (100 kilotons) and 10 megatons. For yields less than 100 kilotons it may be preferable to scale in a similar manner from data given in Table 9.68 for a 20-kiloton surface burst. In this case, the contours for a fission yield of W kilotons can be obtained by multiplying the data in Table 9.68, including the dose rates, by the factor $(W/20)^{1/3}$. In general, if the atomic cloud does not reach the tropopause or is not significantly flattened by it, scaling should be done from the 20-kiloton surface burst data in Table 9.68; however, if the cloud does reach the tropopause, scaling from the 1-megaton values in Table 9.71 (or Fig. 9.72) will give better results.

9.76 The scaling procedures described above will apply (approximately) provided the effective wind velocity is always 15 miles per hour. If the actual effective wind velocity is different from this value, an approximate correction can be made in the following manner,

especially at fairly great distances from ground zero. Suppose that with the 15-mile per hour effective wind, the contour for a certain reference dose rate extends 120 miles downwind. Then, for an effective wind of 20 miles per hour, the corresponding distance for the same value of the reference dose rate will be roughly $(20/15) \times 120 = 160$ miles.

9.77 The results described above (§ 9.71, *et seq.*) are based on the supposition that the fission yield and the total energy yield are equal, such as would be the case if all the energy of the explosion were derived from fission. In some high-yield weapons, however, part of the energy is produced by thermonuclear (fusion) reactions which do not contribute to the radioactivity of the fallout (§§ 1.13, 1.53). Allowance for this fact can be made in the following manner. Suppose the *total* energy yield of the explosion is W megatons, and let f represent the fraction of this energy due to fission. The calculations are first made, as described in the preceding paragraphs, for a *fission* yield of W megatons; the reference dose rate, for any specified distance, is then multiplied by f to give the required reference dose rate at that distance.

Factors Influencing Fallout Contour Pattern

9.78 The contamination contour pattern near ground zero can be predicted with moderate reliability, but it is almost impossible to forecast an accurate pattern of the fallout of the small radioactive particles present in the atomic cloud. In addition to such obvious variables as the fission energy yield and the height of burst, the meteorological conditions and the complex wind pattern at altitudes from perhaps 80,000 or 100,000 feet down to ground level will have important effects. It will be shown later (§ 9.133) that it is possible to estimate, to some extent, the influence of the wind on the general direction in which the fallout will travel, and the contours in Fig. 9.72 include an idealized estimate of this influence. However, there is always a possibility of a sudden and unexpected change in the prevailing winds at higher altitudes, such as have occurred occasionally in nuclear weapons tests.

9.79 One factor about which there is considerable uncertainty, but which plays an important part in the distribution of fallout contamination, is the size of the particles in the atomic cloud. Many of the particles are a few thousandths part of an inch (or less) in diameter and these may take a day or more to fall to earth. During this time they will have traveled some hundreds of miles from the point of burst. The radioactive fallout can thus produce serious contamination

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of the ground at such distances from the nuclear explosion that all other effects—blast, shock, thermal radiation, and initial nuclear radiation—are undetectable.

9.80 It is true that the longer the cloud particles remain suspended in the air, the less will be their activity when they reach the ground. But the total quantity of contaminated material produced by the surface burst of a high-fission-yield (megaton range) weapon is so large, that the activity may still be great even after it has decreased due to the lapse of time. It is for this reason, as well as because of the vast areas affected, that the residual nuclear (fallout) radiation from such an explosion must now be regarded as one of the major effects of nuclear weapons.

9.81 If other conditions, such as fission yield, height of burst, and wind pattern, were the same, an atomic cloud consisting mainly of fairly large particles would lead to a relatively small area of high contamination. On the other hand, if most of the particles are very small, the contaminated area would be much greater, although the radiation intensities, especially farther from ground zero, would not be so large. They might, nevertheless, be large enough to represent a hazard.

9.82 It is evident, therefore, that the fallout contour pattern will be greatly dependent upon the size distribution of the particles in the atomic cloud. And this, in turn, will depend, in a manner that is not yet understood, on the nature of the terrain. There is little doubt that a surface burst in a city will result in a particle size distribution, and consequently a fallout, quite different from that which would follow an exactly equivalent explosion in the open country. In any case, the nature of the underlying ground, both in a city and in the country, would probably influence the particle size characteristics of the atomic cloud.

9.83 Ideally, the fallout contours will be elliptical (or cigar-shaped), as shown in Fig. 9.72, extending downwind from the point of burst, with the long axis in the direction of the average wind. If there is a change in the wind pattern as the particles travel away from ground zero, the contours may be bent to the shape of a banana or like that of a boomerang. However, even in the ideal case of elliptical contours, the dose rates at various distances will depend upon the effects of all the factors mentioned above and may vary according to the existing conditions.

9.84 It was mentioned earlier (§ 9.70) that a combination of circumstances, e. g., atmospheric conditions and terrain, can often lead to somewhat higher deposition of fallout at certain localities (hot

spots). Thus, the radiation intensity within a region of heavy fallout may be expected to vary from point to point, so that the contours in Fig. 9.72, which imply a steady decrease in the dose rate as the distance from the explosion center becomes greater, are idealized. They represent a general average behavior from which variations may occur due to such factors as air currents, rain, snow, and other meteorological conditions. By dispersing the fallout, strong winds near the surface would decrease the amount of contamination in certain areas, but the effect might well be to transfer the radioactive particles to a previously uncontaminated (or slightly contaminated) region. The possible effect of a rainfall situation in the case of an air burst was discussed in § 9.50. Somewhat similar circumstances could affect the distribution of the contamination after a surface burst.

9.85 Another aspect of fallout which is not shown in Fig. 9.72 is the harmful action of beta-particle emitters in contact with the skin. The doses to which the contours refer are essentially due to gamma radiation from the fission products and other bomb residues. If the fallout dust is allowed to remain on the skin for any appreciable time, the beta particles can cause serious burns, in addition to the other consequences of radiation exposure (see Chapter XI).

Contamination from the High-Yield Explosion of March 1, 1954

9.86 The foregoing remarks may be supplemented by a description of the observations on the fallout contamination of the Marshall Islands made in connection with the high-yield test explosion at Bikini Atoll on March 1, 1954.[6] The device was detonated on a coral island and the resulting fallout, consisting of radioactive particles ranging from about one-thousandth to one-fiftieth of an inch in diameter, seriously contaminated an elongated, cigar-shaped area extending approximately 220 (statute) miles downwind and varying in width up to 40 miles. In addition, there was a severely contaminated region upwind extending some 20 miles from the point of detonation. A total area of over 7,000 square miles was contaminated to such an extent that survival might have depended upon evacuation of the area or taking protective measures.

9.87 From radiation dose measurements made at a number of stations, and from calculations based on known physical data and previous experience, reasonably good estimates could be made of several fallout contours. These are shown in somewhat idealized

[6] "The Effects of High-Yield Nuclear Explosions." A report by the U. S. Atomic Energy Commission, Government Printing Office, February, 1955.

form in Fig. 9.87, for the total gamma radiation exposure (or accumulated dose) in roentgens that would be received in a period of 36 hours following the explosion. It should be noted that the doses, to which the contours in Fig. 9.87 refer, are values calculated from instrument records. They represent the maximum possible exposure and would be received only by those individuals who remained in the open, with no protection against the radiation, for the whole time. Any kind of shelter, e. g., within a building, or evacuation of the area would have reduced the dose received. On the other hand, persons remaining in the area for a longer period than 36 hours after the explosion would have received larger doses of the residual radiation.

9.88 A radiation dose of 700 roentgens spread over a period of 36 hours would probably prove fatal in nearly all cases. It would appear, therefore, that following the test explosion of March 1, 1954, there was sufficient radioactivity from the fallout in a downwind belt about 140 miles long and up to 20 miles wide to have seriously threatened the lives of nearly all persons who remained in the area for at least 36 hours following the detonation without taking protective measures of any kind. At distances of 220 miles or more downwind, the number of deaths due to radiation would have been negligible, although there would probably have been many cases of sickness resulting in temporary incapacity.

9.89 The period of 36 hours after the explosion, for which Fig. 9.87 gives the accumulated radiation exposures, was chosen somewhat arbitrarily as a time when essentially all the fallout remaining in the general vicinity will have descended to earth. It should be understood, however, as has been frequently stated earlier in this chapter, that the radiations from fission products will continue to be emitted for a long time, although at a steadily decreasing rate. The persistence of the external gamma radiation may be illustrated in connection with the March 1, 1954, test by considering the situation at two different locations in Rongelap Atoll in the Marshall Islands. Fallout began about 4 to 6 hours after the explosion and continued for several hours.

9.90 The northwestern tip of the atoll, 100 miles from the point of detonation, received 2,300 roentgens during the first 36 hours after the fallout started. This was the heaviest fallout recorded at the same distance from the explosion. About 25 miles south, and 115 miles from ground zero, the indicated dose over the same period was only 150 roentgens. The inhabitants of Rongelap Atoll were in this area, and were exposed to radiation dosages up to 175 roentgens before they were evacuated some 44 hours after the fallout began (see § 11.47). The

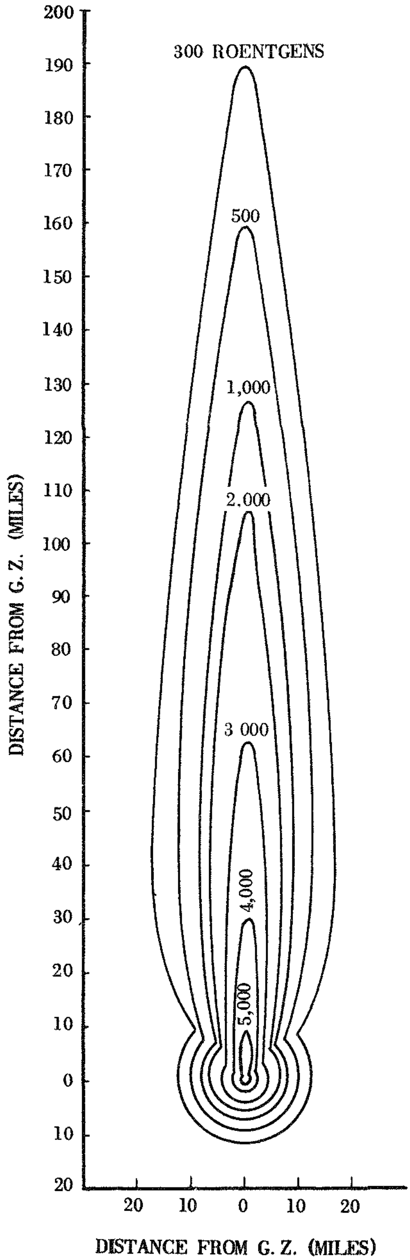

Figure 9.87. Idealized total (accumulated) dose contours from fallout in first 36 hours after the high yield explosion at Bikini Atoll on March 1, 1954.

maximum theoretical exposures in these two areas of the atoll for various time intervals after the explosion, calculated according to the generally accepted decay rule (§§ 9.7, 9.112), are recorded in Table 9.90.

TABLE 9.90

CALCULATED RADIATION DOSES AT TWO LOCATIONS IN RONGELAP ATOLL FROM FALLOUT FOLLOWING THE MARCH 1, 1954 TEST AT BIKINI

Exposure period after the explosion	Accumulated dose in this period (roentgens)	
	Inhabited location	Uninhabited location
First 36 hours	140	2, 150
36 hours to 1 week	101	1, 310
1 week to 1 month	73	950
1 month to 1 year	83	1, 080
Total to 1 year	397	5, 490
1 year to infinity	About 129	About 1,680

9.91 It must be emphasized that the calculated values given in Table 9.90 represent the maximum doses at the given locations, since they are based on the assumption that exposed persons remain out-of-doors for 24 hours each day and that no measures are taken to remove radioactive contamination (see § 12.81, *et seq.*). Further, no allowance is made for weathering, i. e., washing of fallout particles into the soil by rainfall, or the possible dispersal of the particles by winds. For example, the dose rates measured on parts of the Marshall Islands on the 25th day following the explosion were found to be about 40 percent less than the computed values. Rains were known to have occurred, after the second week, and these were probably responsible for the major decrease in the contamination.

9.92 In concluding the present discussion of fallout contamination, it may be noted that the 36-hour dose contours shown in Fig. 9.87, representing the fallout pattern in the vicinity of Bikini Atoll after the high-yield explosion of March 1, 1954, as well as the 1-hour (reference) dose-rate contours in Fig. 9.72, can be regarded as more or less typical, so that they may be used for planning purposes. Nevertheless, it should be realized that they cannot be taken as an absolute guide. The particular situation which developed in the Mar-

shall Islands was the result of a combination of circumstances involving the energy yield of the explosion, the height of burst, the nature of the surface below the point of burst, the wind system over a large area and to a great height, and other meteorological conditions. A change in any one of these factors could have affected considerably the details of the fallout pattern.

9.93 In other words, it should be understood that the fallout situation described above is one that *can* happen, but is not necessarily one that *will* happen, following the surface burst of a high-fission-yield weapon. The general direction in which the fallout will move can be estimated fairly well if the wind pattern is known. However, the fission yield of the explosion or the height of burst, in the event of a nuclear attack, are unpredictable. Consequently, it is impossible to determine in advance how far the seriously contaminated area will extend, although the time at which the fallout will commence at any point could be calculated if the effective wind velocity and direction were known.

9.94 In spite of the uncertainties concerning the exact fallout pattern, there are highly important conclusions to be drawn from the results described above. One is that the residual nuclear radiation can, under some conditions, represent a serious hazard at great distances from a nuclear explosion, well beyond the range of blast, shock, thermal radiation, and the initial nuclear radiation. Another is that plans can be made to minimize the hazard, but such plans must be flexible, so that they can be adapted to the particular situation which develops after the attack.

Radiological Warfare

9.95 For some time, consideration has been given to the possibility of using radioactive material deliberately as an offensive weapon in what is called "radiological warfare." The basic idea is that radioactive contamination of areas, factories, or equipment would make their use either impossible or very hazardous without any accompanying material destruction. To be effective, a radiological warfare agent should emit gamma radiations and it should have a half life of a few weeks or months. Radioisotopes of long half life give off their radiations too slowly to be effective unless large quantities are used, and those of short half life decay too rapidly to provide an extended hazard.

9.96 Even if a radioisotope with suitable properties and which could be readily manufactured were selected as a radiological war-

fare agent, the problems of production, handling, and delivery of the weapon emitting intense gamma radiation would not be easily solved. In addition, stockpiling the radioactive material would present a difficulty. Other weapons can be prepared in advance, ready for an emergency. They can be kept for a long time without suffering deterioration. This is not true for radiological warfare agents, for natural decay would result in a continuous loss of active material. The production of a specific radioisotope is a slow process, at best, and so the continual and unavoidable loss would be a serious drawback.

9.97 The situation has undergone a change with the development of bombs having high fission energy yields. The explosion of such bombs at low altitudes can cause radioactive contamination over large areas that are beyond the range of physical damage. Consequently, they are, in effect, weapons of radiological warfare. Instead of preparing and stockpiling the contaminating agent in advance, with its attendant difficulties, the radioactive substances are produced by fission at the time of the explosion. Radiological warfare has thus become an automatic extension of the offensive use of nuclear weapons of high yield.

Contamination of Areas

9.98 It was suggested in § 9.95 that radioactive contamination could deny the use of considerable areas for an appreciable period of time. There are two aspects of this situation which merit consideration. First, the direct effect of the radiation exposure on human beings who might have to live or work in a contaminated region, and second, the indirect effect due to the consumption of food grown (and animals raised) in such an area. The methods for calculating exposure doses from fission products, assuming no protection, have been given in this chapter (see also Figs. 12.107 and 12.108). The time that may be spent at a given location can thus be determined, provided some limit has been set concerning the total exposure dose. The value of such an emergency dose cannot be prescribed in advance, since it will depend entirely on the conditions existing in the particular circumstances.

9.99 In contaminated agricultural areas, the hazard to workers could be reduced by turning over the earth, so as to bury the fallout particles. But there still remains the matter of the absorption of fission products from the soil by plants and their ultimate entry into the human system in food. It is known that some elements are taken

up more easily than others, but the actual behavior depends on the nature of the soil and other factors. This highly complex problem is being studied to determine the extent of the hazard which would result from the absorption of fission products by plants in various circumstances and how it might be minimized.

Contamination in Subsurface Bursts

9.100 The extent of the contamination due to residual nuclear radiation following a subsurface explosion will depend primarily on the depth of the burst. If the explosion occurs at a sufficient depth below the surface, essentially none of the bomb residues and neutron-induced radioactive materials will escape into the atmosphere. There will then be no appreciable fallout. On the other hand, if the burst is near the surface, so that the ball of fire actually breaks through, the consequences, as regards fallout, will not be very greatly different from those following a surface burst.

9.101 There will, in fact, be a gradual transition in behavior from a high air burst, at one extreme, where all the radioactive bomb residues are dissipated in the atmosphere, to a deep subsurface burst, at the other extreme, where the radioactive materials remain below the surface. In neither case will there be any significant local fallout. Between these two extremes are surface bursts or low air bursts which will be accompanied by extensive contamination due to fallout. These merge into shallow subsurface bursts, for which the behavior is similar. With increasing depth of explosion, more of the radioactive bomb residues remain in the vicinity of the burst point, i. e., in and around the crater, and proportionately less goes into the upper atmosphere to descend at a distance as fallout.

9.102 Since a shallow burst, in which the fireball emerges from the ground, is essentially similar to a low surface burst, in which a large part of the fireball touches the earth, this type of nuclear explosion need not be discussed further. The case of interest, however, is that of a subsurface burst at such a depth that the ball of fire does not emerge, yet a considerable amount of dirt (or water) is thrown up as a column into the air (§ 2.67).

9.103 It may be noted that some contribution to the residual nuclear radiations following a subsurface detonation is made by the radioisotopes, e. g., sodium-24 (§ 9.21), formed by neutron capture. However, as with a surface burst, this is so small in comparison with the radiations from the fission products that it may be ignored.

9.104 In the case of an underground explosion at a moderate depth there will be considerable crater formation. Much of the radioactive material will remain in the crater area, partly because it does not escape and partly because the larger pieces of contaminated rock, soil, and debris thrown up into the air will descend in the vicinity of the explosion. The finer particles produced directly or in the form of a base surge (§ 2.71) will remain suspended in the air and will descend as a fallout at some distance from ground zero.

9.105 The fallout contour pattern will be dependent upon the fission energy yield, the depth of burst, the nature of the soil, and also upon wind and weather conditions. Other circumstances being more or less equal, the contamination in the crater area following a subsurface burst will be about the same as for a surface explosion of equal fission yield. However, the total contaminated area will be greater for the (shallow) subsurface burst because a larger amount of fission products is present in the fallout.

9.106 The fallout following a shallow underwater burst, of the type used in the Bikini BAKER test in July 1946 (§ 2.49), will be very much like that of an underground explosion, as just described. In this particular test, the cloud did not ascend as high as in an air burst of the same energy yield. As a result, the fallout, which was in effect a radioactive rain, commenced to descend very soon after the explosion. In fact, the first fallout (or rain-out) reached the surface of the lagoon within about a minute of the detonation. A large proportion of the fission product (and other) activity was thus precipitated in a short time within a radius of a few thousand yards of the approximately 20-kiloton burst.

9.107 In the Bikini BAKER test the base surge, consisting of a contaminated cloud or mist of small water droplets, formed 10 to 12 seconds after the explosion and moved rapidly outward (§ 2.57). This undoubtedly contributed to the radioactivity deposited on the ships in the lagoon, but the base surge is now thought to be less significant as a source of contamination than the water (rain-out) which descended from the cloud system.

9.108 An important difference between an underwater burst and one occurring under the ground, is that the radioactivity remaining in the water is gradually dispersed, whereas that in ground is not. As a result of diffusion of the various bomb residues, mixing with large volumes of water outside the contaminated area, and natural decay, the radiation intensity of the water in which a nuclear explosion has occurred will decrease fairly rapidly. Some indication of the rate of decrease and of the spread of the active material is pro-

vided by the data in Table 9.108, obtained after the Bikini BAKER test. Thus, within 2 or 3 days the radioactivity had spread over an area of about 50 square miles, but the maximum radiation dose rate was then so low that the area could be traversed without danger.

TABLE 9.108

DIMENSIONS AND DOSE RATE OF CONTAMINATED WATER AFTER THE 20-KILOTON UNDERWATER EXPLOSION AT BIKINI

Time after explosion (hours)	Contaminated area (square miles)	Mean diameter (miles)	Maximum dose rate (roentgens per hour)
4	16. 6	4. 6	3. 1
38	18. 4	4. 8	0. 42
62	48. 6	7. 9	0. 21
86	61. 8	8. 9	0. 042
100	70. 6	9. 5	0. 025
130	107	11. 7	0. 008
200	160	14. 3	0. 0004

9.109 In addition to the factors mentioned above, the settling of fission products to the bottom of the lagoon contributed to the decrease in activity after the BAKER test. From an examination of bottom material made a few days after the explosion, it appeared that a considerable proportion of the bomb residues must have been removed from the water in this manner. The results indicated that the major deposition had taken place within a week of the underwater explosion, and that the area covered was then about 60 square miles. Although the total amount of radioactivity on the bottom of the lagoon was very high, it was so widely distributed that it did not represent a hazard to marine life. Observations made several months later indicated that there was little or no tendency for the contaminated material to spread. But this may be attributed, in part at least, to the landlocked nature of Bikini Lagoon.

TECHNICAL ASPECTS OF RESIDUAL NUCLEAR RADIATION [7]

DECAY OF FISSION PRODUCTS

9.110 The mixture of radioisotopes constituting the fission products is so complex that a mathematical representation of the rate of

[7] The remaining sections of this chapter may be omitted without loss of continuity.

decay in terms of the individual half lives is impractical. However, it has been found experimentally that for the period from several minutes to 2 or 3 years after detonation the *over-all* rate of radioactive disintegration (or rate of emission of radiations) by the fission products can be represented, to a fair degree of accuracy, by the relatively simple expression

$$\text{Rate of disintegration} = A_1 t^{-1.2}, \qquad (9.110.1)$$

where t is the time after formation of the fission products, i. e., the time after the explosion, and A_1 is a constant factor, defined as the rate of disintegration at unit time, that is dependent upon the quantity of fission products. This equation can also be used, with appropriate values for A_1, to give the rate of emission either of gamma rays or of beta particles. A beta particle is liberated in each act of disintegration, but gamma ray photons are produced in about one-half only of the fission product disintegrations, the fraction varying with the time after the explosion.

9.111 In considering the radiation dose (or dose rate) due to fission products, e. g., in fallout, the gamma rays, because of their long range and penetrating power, are of greater significance than the beta particles, provided the radioactive material is not actually on the skin or within the body. Consequently, the beta radiation can be neglected in estimating the variation with time of the dose rate from the residual nuclear radiation. If the fraction of fission product disintegrations accompanied by gamma ray emission and the energy of the gamma ray photons remained essentially constant with time, the dose rate, e. g., in roentgens per hour, would be directly related to the rate of emission of gamma rays. As mentioned in § 9.34, this is not the case. The gamma rays in the early stages of fission product decay have, on the average, higher energies than in the later stages. However, for the periods of practical interest, commencing a few hours after the explosion, the mean energy of the gamma ray photons may be taken as essentially constant, at about 0.7 Mev.

9.112 Although the fraction of gamma emitters varies with time, a fair approximation based on equation (9.110.1) is that, at any time t after the explosion,

$$\text{Gamma radiation dose rate} = R_1 t^{-1.2}, \qquad (9.112.1)$$

where R_1 is a constant. Physically, R_1 is equivalent to the (reference) dose rate at unit time. As a general rule, the time t is expressed in hours, and then R_1 is the reference dose rate at 1 hour after the explosion. If R_t represents the dose rate from a certain quantity of

fission products at t hours after the explosion, then, from equation (9.112.1),

$$\frac{R_t}{R_1}=t^{-1.2}, \tag{9.112.2}$$

or, upon taking logarithims,

$$\log\frac{R_t}{R_1}=-1.2\log t. \tag{9.112.3}$$

9.113 It follows from equation (9.112.3) that a log-log plot of R_t/R_1 against t should give a straight line with a slope of -1.2. When $t=1$, i. e., at 1 hour after the explosion, $R_t=R_1$, so that $R_t/R_1=1$; this is the basic reference point through which the line of slope -1.2 is drawn in Fig. 9.8.

9.114 If the time, t, is in hours, the radiation exposure dose rates R_t and R_1 are expressed in roentgens per hour. Then, the total dose in roentgens received from a given quantity of fission products during any specified period after the explosion can be readily obtained by direct integration of equation (9.112.2). For example, for the interval from t_a to t_b hours after the detonation,

$$\begin{aligned}\text{Total dose}&=R_1\int_{t_a}^{t_b}t^{-1.2}dt\\&=\frac{R_1}{0.2}\left[\frac{1}{t_a^{0.2}}-\frac{1}{t_b^{0.2}}\right]\end{aligned} \tag{9.114.1}$$

Hence, if the reference dose rate, R_1 roentgens per hour, at 1 hour after the explosion, is known the total dose (in roentgens) for any required period can be calculated.

9.115 The curve in Fig. 9.12 is derived from equation (9.114.1) with t_a being taken as 0.0167 hour, i. e., 1 minute, which is the time when the residual nuclear radiation is postulated as beginning. Hence, Fig. 9.12 gives the total radiation dose received up to any specified time after the detonation, assuming exposure during the whole period.

9.116 Another application of equation (9.114.1) is to determine the time which an individual can stay in a location contaminated by fission products without receiving more than a specified dose of radiation. In this case, the total dose is specified; t_a is the known

time of entry into the contaminated area and t_b is the required time at (or before) which the exposed individual must leave. In order to solve this problem with the aid of equation (9.114.1), it is necessary to know the reference dose rate, R_1. This can be obtained from equation (9.112.2) if the dose rate, R_t, is measured at any time, t, after the explosion, e. g., at the time of entry. The results can be expressed graphically as in Figs. 12.107 and 12.108.

9.117 In principle, equation (9.114.1) could be used to estimate the total dose received from fallout in a contaminated area, provided the whole of the fallout arrives in a very short time. Actually, the contaminated particles may descend for several hours, and without knowing the rate at which the fission products reach the ground, it is not possible to make a useful calculation. When the fallout has ceased, however, equations (9.112.2) and (9.114.1) may be employed to make various estimates of radiation doses, provided one measurement of the dose rate is available.

Fission Product Activities in Curies

9.118 The rate at which a radioactive material disintegrates (or decays), and hence the rate at which it emits beta particles or gamma rays, is generally stated in terms of a unit called the "curie." It is defined as the quantity of radioactive material undergoing 3.7×10^{10} disintegrations per second. This particular rate was chosen because it is (approximately) the rate of disintegration of 1 gram of radium. Since the activities of fission products from a nuclear explosion are very high, it is more convenient to use the "megacurie" unit. This is equal to 1 million curies and corresponds to disintegrations at a rate of 3.7×10^{16} per second.

9.119 As stated above, the gamma rays are, in general, more significant biologically than the beta particles from fission products. Consequently, the fission product activity as expressed in (gamma) curies is a measure of the rate of emission of gamma ray photons, rather than of the rate of disintegration. Using equation (9.110.1) as the basis, the total gamma activities of all the fission products from a 1-megaton explosion have been calculated for various times after the detonation. The results are given in Table 9.119.

Radiation Dose Rates Over Contaminated Surfaces

9.120 If an area is uniformly contaminated with any radioactive material of known activity (in curies), it is possible to calculate the

TABLE 9.119

TOTAL GAMMA RADIATION ACTIVITY OF FISSION PRODUCTS FROM A 1-MEGATON EXPLOSION

Time after explosion	*Activity (megacuries)*
1 hour	300,000
1 day	6,600
1 week	640
1 month	110
1 year	5.5

gamma-radiation dose rate at various heights above the surface, provided the average energy of the gamma-ray photons is known. The results of such calculations, assuming a contamination density of 1 (gamma) megacurie per square mile, for gamma rays having energies of 0.7 Mev, 1.5 Mev, and 3.0 Mev, respectively, are represented in Fig. 9.120. The curve for 0.7 Mev is approximately applicable to a surface contaminated with fission products. If the actual contamination density differs from 1 megacurie per square mile, the ordinates in the figure would be multiplied in proportion.

9.121 It may be noted that in the calculations upon which the curves in Fig. 9.120 are based, the scattering of gamma radiation back to the ground by interaction with the oxygen and nitrogen in the air was neglected. This would tend to make the observed dose rates larger than those given. On the other hand, it was assumed that the surface over which the contamination is distributed is perfectly flat. For moderately rough terrain, the dose rate at a specified height is less than for a flat surface. In practice the two deviations largely compensate one another, so that Fig. 9.120 gives a relatively good value for the dose rate in air above an uneven surface.

9.122 The dose rate at greater heights above the ground, such as might be observed in an aircraft, can be estimated with the aid of Fig. 9.122. The curve gives the attenuation factor for fission product radiation as a function of altitude. It applies in particular to a uniformly contaminated area that is large compared to the altitude of the aircraft. If the dose rate near the ground is known, then the value at any specified altitude can be obtained upon dividing by the attenuation factor for that altitude. On the other hand, if the dose rate is measured at a known altitude, multiplication by the attenuation factor gives the dose rate near the ground.

9.123 A possible use of the curve in Fig. 9.122 is to determine the dose rate and contamination density of the ground from data obtained by means of an aerial survey (see § 12.77). For example, suppose a radiation measuring instrument suspended from an aircraft at a

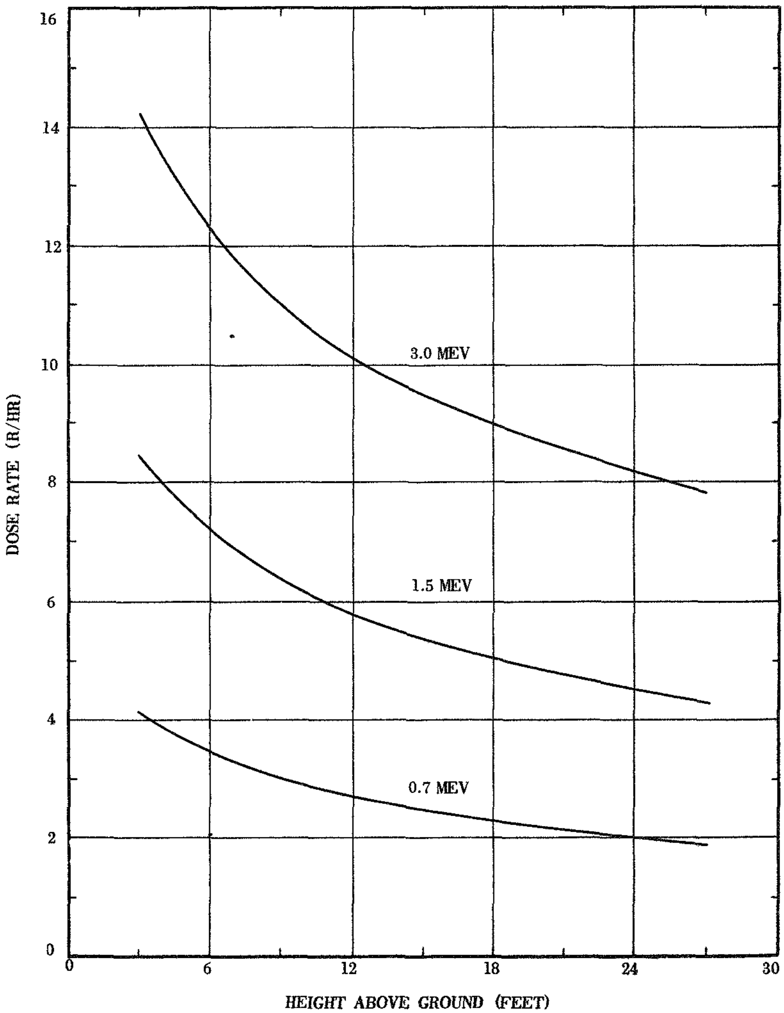

Figure 9.120. Dose rate of gamma radiation near ground with uniform contamination density of 1 megacurie per square mile.

height of 1,000 feet showed a radiation dose rate of 0.24 roentgen per hour. The attenuation factor for this altitude is 30 and so the dose rate on the ground is approximately $0.24 \times 30 = 7.2$ roentgens per hour. It is seen from Fig. 9.120 that for a contamination density of 1 megacurie per square mile the dose rate near the ground is about 4 roentgens per hour. Hence, in the present case, the contamination density is approximately $7.2/4 = 1.8$ megacuries per square mile.

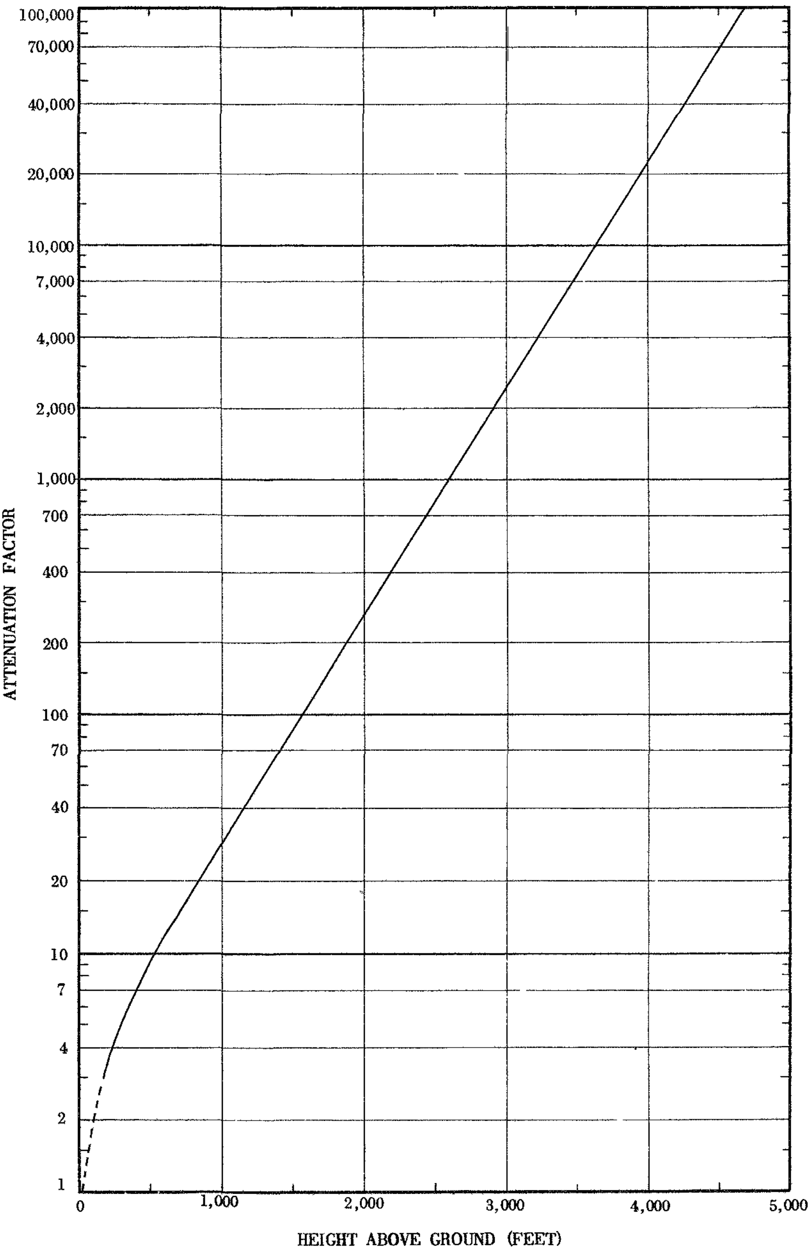

Figure 9.122. Altitude attenuation factor for fission product radiation from the ground.

9.124 The dose rates from gamma radiations of various energies above the surface of water uniformly contaminated with a density of 1 (gamma) curie per cubic yard (1 megacurie per million cubic yards) are shown in Fig. 9.124a. The curve for 0.7-Mev energy may be regarded as applicable to contamination by fission products. The dose rates at various altitudes can be estimated by the use of the attenuation factors in Fig. 9.122. Within the water itself, in which the contamination is assumed to be uniformly distributed, the dose rates are given by Fig. 9.124b, as a function of gamma-ray energy. From the measurement of dose rate made in an aircraft at a known altitude, it is possible to calculate the contamination density of the water, using Figs. 9.122 and 9.124a. Then, from Fig. 9.124b, the dose rate in the water can be evaluated.

Rate of Fall of Particles

9.125 An important aspect of the fallout problem is a theoretical study of the distribution of particle size as a function of distance from the region of the explosion. A simple treatment will be given here, which, although approximate, provides a picture that is believed to be qualitatively correct. For purposes of illustration, it will be supposed that a weapon of high-energy yield is exploded near the surface of the ground. Although the particles will descend from the atomic cloud at all heights between 60,000 and 100,000 feet, at least, it will be postulated, in order to simplify the calculations, that they all commence to fall when they reach the average height of 80,000 feet.

9.126 The rate of fall of small particles in air from great heights under the influence of gravity can be determined approximately by means of Stokes's law, in the form,

$$\text{Rate of fall} = 0.35 d^2 \rho \text{ feet per hour,} \qquad (9.126.1)$$

where ρ is the density of the particle in grams per cubic centimeter and d is its diameter in microns.[8] This expression applies moderately well for particles from 5 to 300 microns, i. e., 5×10^{-4} to 3×10^{-2} centimeters, in diameter. For larger particles, the rates of fall are actually slower than are given by the simple Stokes's law. Assuming that the fallout particles have the same density as sand, i. e., 2.6 grams per cubic centimeter, the approximate times required for particles of various diameters to descend to earth from a height of 80,000 feet, as calculated from equation (9.126.1), are given in Table 9.126. Particles

[8] 1 micron is a one-millionth part (10^{-6}) of a meter or one ten-thousandth (10^{-4}) of a centimeter.

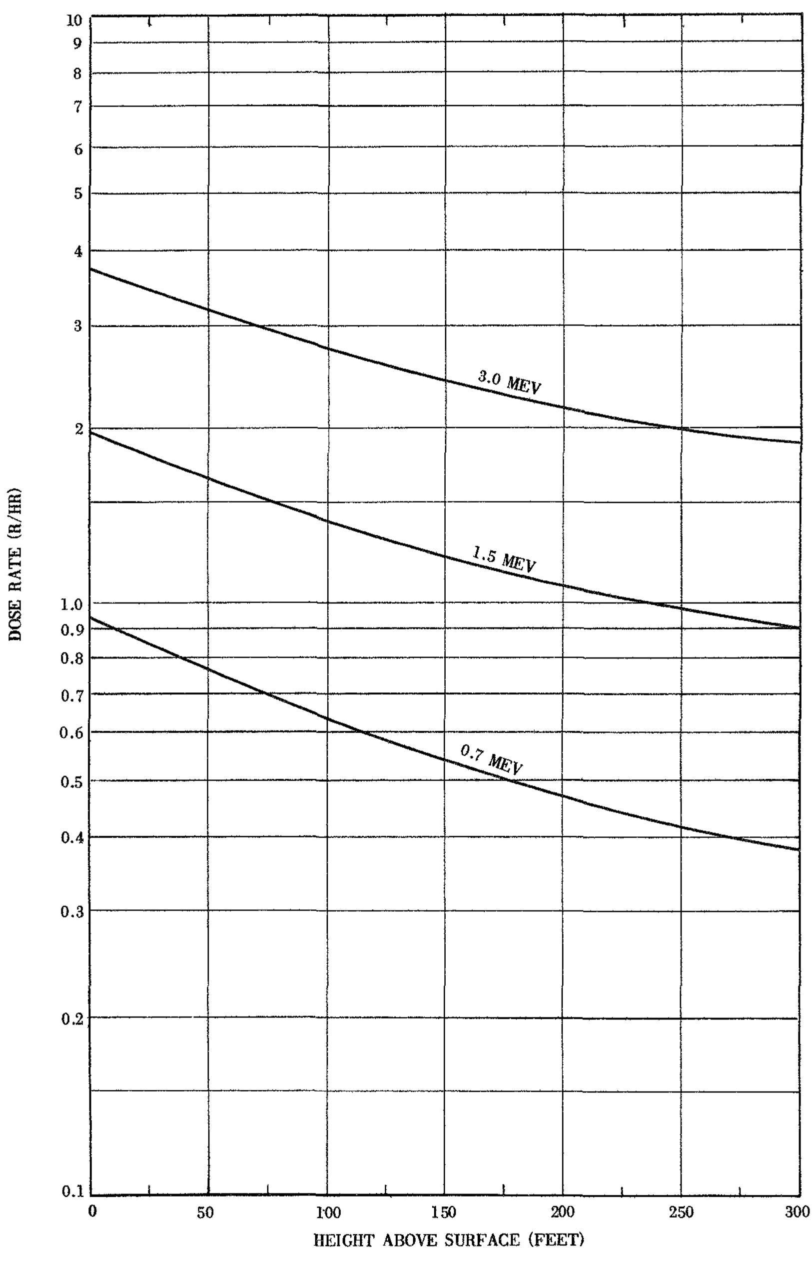

Figure 9.124a. Dose rate of gamma radiation near surface of water with uniform contamination density of 1 curie per cubic yard.

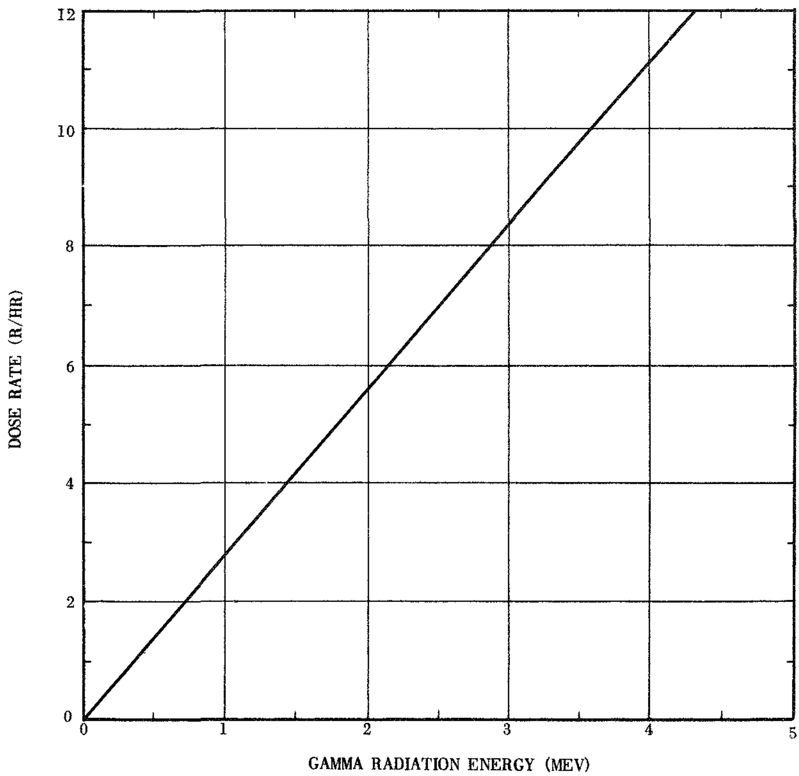

Figure 9.124b. Dose rate of gamma radiation within a large volume of water with uniform contamination density of 1 curie per cubic yard.

smaller than 5 microns in diameter are seriously affected by Brownian movement, resulting from collisions with air molecules, so that some of them, as seen earlier, remain suspended for very long periods. The

TABLE 9.126

APPROXIMATE TIMES FOR PARTICLES TO FALL FROM 80,000 FEET

Particle diameter (microns)	*Time of fall (hours)*
340	0.75
250	1.4
150	3.9
75	16
33	80
16	340
8	1,400
5	3,400

rate of fall of even larger particles is affected by turbulence of the air.

9.127 If all the particles descended from the same level, the data in Table 9.126 (or calculated from equation (9.126.1)) could be used to estimate the variation of particle size in the fallout as a function of the distance from ground zero. The actual distance would depend upon the height of the cloud from which the particles fell, since this determines the time of fall, and upon the effective wind velocity. It is, nevertheless, possible to plot a generalized curve, such as that in Fig. 9.127; the distance from ground zero is equal to the time of fall from 80,000 feet multiplied by the average (effective) wind velocity, taken as 15 miles per hour. It is evident that particles having diameters in excess of about 250 microns (0.01 inch) or so, may be expected to fall within a relatively short distance of ground zero. Smaller particles, however, can travel much greater distances before descending to earth as fallout.

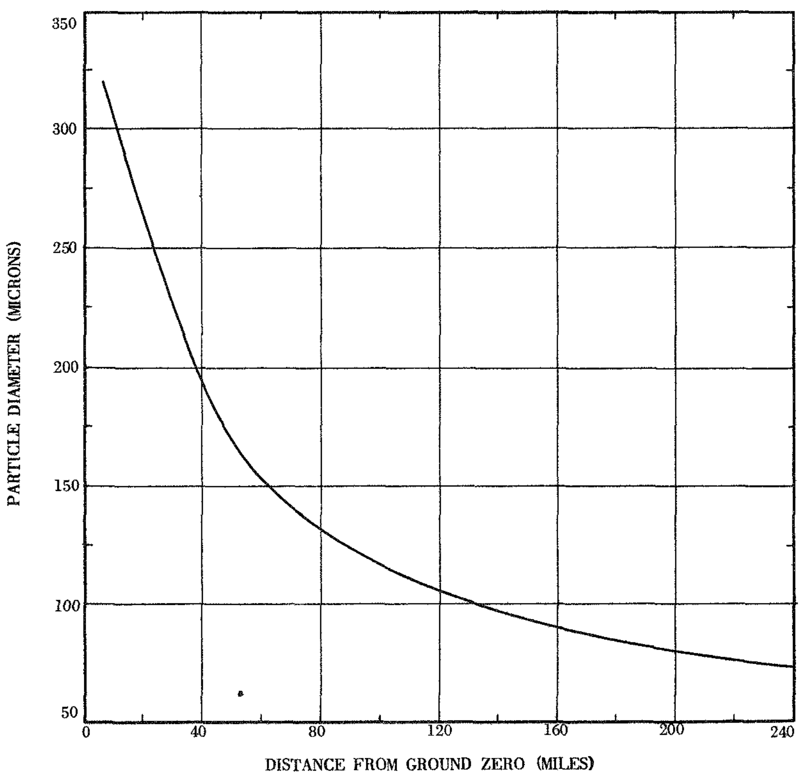

Figure 9.127. Distance traveled by particles of various sizes in fallout (fall from 80,000 feet with an assumed 15 mph effective wind).

9.128 In practice, the ideal conditions, upon which Fig. 9.127 is based, do not prevail. For example, Stokes's law is not obeyed, the particles do not all rise to the same height in the cloud before they begin to fall, and the wind velocity is variable. Further, irregularities in shape and the mutual adhesion of smaller particles, as well as turbulence of the air, will affect the rate of fall. Consequently, after a nuclear explosion the variation of particle size with distance is not as uniform as is implied by the foregoing discussion. It is probable. however, that the curve in Fig. 9.127 gives a good general idea of the distribution of particle size with distance from ground zero.

9.129 Disregarding the approximations made in deriving the curve in Fig. 9.127, the distances at which particles of various sizes are found depend on the postulated effective wind velocity (15 miles per hour) and the average height from which the particles are assumed to fall (80,000 feet). For an explosion of lower energy yield, the cloud will not rise so high and so particles of any given size will reach the earth sooner. The respective distances from ground zero will then be less than in Fig. 9.127, for the same wind velocity. On the other hand, a higher effective wind velocity will result in an increase in the distance traveled by particles of any specified size before reaching the ground.

9.130 From the standpoint of radioactive contamination, the surface area of the particles is of some significance, in addition to their rate of fall. Many fallout particles collected after test explosions have shown fairly uniform distribution of the radioactivity, but in others the activity has been found only near the surface (§ 2.21). However, with the object of simplifying the subsequent treatment, it will be assumed that the contamination is of the latter type and that the thickness of the radioactive layer is always the same. The total radioactivity carried by particles of a given size will then depend on the proportion of the total area associated with that size group. In order to make the calculations, it is necessary to know the size distribution among the fallout particles, i. e., the proportion in each size group. As a rough guide, in default of more definite information, the distribution is taken to be the same as in the soil over which the detonation occurs.

9.131 On the basis of the foregoing assumptions, the results in Table 9.131 have been obtained. The four particle size groups are based on the diameters in the first column of Table 9.126, and the fallout periods then correspond to the times of fall from a height of 80,000 feet, as given in the second column of this table. The data in Table 9.131 show that by the end of 16 hours after the explosion

about 50 percent of the total fission product activity will have been deposited on the ground. During this time the particles will have traveled some 240 miles downwind, if the effective wind velocity is 15 miles per hour.

TABLE 9.131

PROPORTION OF ACTIVE MATERIAL DEPOSITED FROM ATOMIC CLOUD FROM 80,000 FEET ALTITUDE

Diameter of particles (microns)	Period of arrival (hours)	Percentage of activity deposited
340	Up to 0.75	3. 8
340–250	0.75 to 1.4	12. 6
250–150	1.4 to 3.9	14. 5
150–75	3.9 to 16	18. 1

9.132 The results in the last column of Table 9.131 give the percentage of the *initial* fission product activity in the various particle size groups. In other words, no allowance is made for the natural radioactive decay during their ascent with the atomic cloud and their descent with the fallout. However, because of this decay, the material deposited on the ground at increasing times after the burst will be less and less active. Thus, Table 9.131 indicates that in the period from 3.9 hours to 16 hours after the explosion about 18 percent of the fission products will reach the earth's surface. But, if allowance is made for natural decay, it is probable that this would represent less than 0.1 percent of the original radioactivity of the atomic cloud.

PREDICTION OF FALLOUT PATH

9.133 Several methods of various degrees of accuracy (and corresponding complexity) have been proposed for plotting the expected path of the fallout on the ground after a nuclear explosion. One of the simplest will be described below.[9] Although the results may not be as precise as could be obtained in other ways, the procedure has the great merit of rapidity and is capable of being carried out even under emergency conditions.[10] The basic information required is a knowl-

[9] U. S. Department of Commerce, Weather Bureau Circular Letter 16–54.
[10] More refined fallout computations are made by hand and special purpose analog computers.

edge (or prognosis) of the mean wind direction and speed in a series of 5,000-foot thick layers of the atmosphere from the earth's surface to the top of the atomic cloud.

9.134 Starting at a point O, representing ground zero, in Fig. 9.134, a vector OA is drawn, indicating the direction and velocity (in miles per hour) of the wind in the first 5,000-foot level from the ground. This is followed by vectors AB, BC, . . ., GH, for successive levels up to the limit of observation, e. g., the top of the cloud, in this case, $8\times 5{,}000=40{,}000$ feet. The line OH then represents the locus of particles which fall from a height of 40,000 feet at various times. The larger particles will be found close to ground zero, soon after the explosion, whereas the smaller particles fall at greater distances, at later times. The line OG is the locus of particles falling from a height of 35,000 feet, since these are not subjected to the wind represented by the vector GH. Similarly, OF is the locus for particles which begin to fall at 30,000 feet, and so on. The average wind for levels up to 40,000 feet is equal to the length of OH divided by the number of 5,000-foot levels, i. e., 8 in this case.

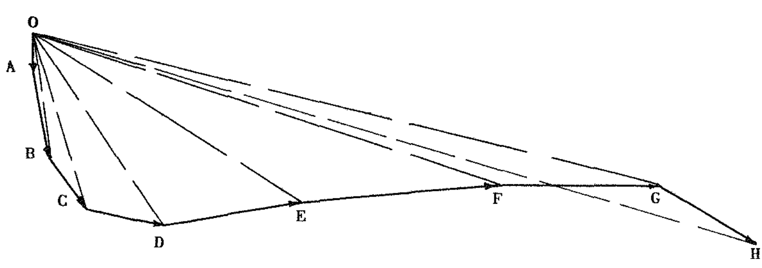

Figure 9.134. Prediction of approximate path of fallout based on wind pattern.

9.135 The region enclosed by the line OH and the various vectors may thus be regarded as providing a rough indication of the general direction of the fallout with respect to ground zero. There is, in addition to the effect of wind, some diffusion of the particles in the atmosphere, which will result in an extension in all directions about the idealized region derived from the wind vector.

9.136 Although Fig. 9.134 gives a general idea of the shape of the fallout area, it does not indicate its over-all extent. If, as is the case considered above, the wind vectors, expressed in miles per hour, are drawn at 5,000-foot levels, OH is the distance traveled by particles descending from the height of 40,000 feet in 8 hours. Similarly, OG is the distance traveled by particles descending from 35,000 feet in 7

hours. Thus, *OAB . . . HO* is dimensionally the approximate area in which particles having diameters of 75 microns (or more) will descend. Such particles fall at the rate of 5,000 feet per hour (or more). Smaller particles fall more slowly and will be found outside the area shown. The loci on the ground of particles descending from various heights will, however, have the same directions as before. Thus, particles with diameters less than 75 microns falling from 40,000 feet will appear along an extension of *OH*, those from 35,000 feet along an extension of *OG*. Hence the general shape of the fallout pattern is related to that in Fig. 9.134, although it covers a larger area.

9.137 It will be apparent that the procedure just described can provide only a rough guide concerning the probable fallout area. In actuality, the particle size distribution will not be known, and the height of the atomic cloud from which the particles descend will not be very certain. In addition, the wind directions and velocities may change with time, and the effect of sharp wind shears in thin layers has been neglected. Finally, there is the fundamental assumption that the wind pattern used in drawing Fig. 9.134 applies to the whole area of significant contamination which may extend as far as 200 miles from ground zero. Rain or snow falling at the time of (or soon after) the detonation will also change the fallout situation, since many radioactive particles will become attached to the drops and descend from various heights at rates which are characteristic of the rain or snow.

9.138 In the event that no upper wind information at (or near) the time of the explosion is available, use may be made of the general pattern to be expected in the given location at the particular time of year. This information, based on observations made at weather stations over long periods, may perhaps be supplemented by visual estimates of the direction of cloud movements at various heights. It is important to emphasize that fallout patterns based on surface winds alone may be completely misleading.

CHAPTER X

WORLD-WIDE FALLOUT AND LONG-TERM RESIDUAL RADIATION

LOCAL AND WORLD-WIDE FALLOUT

INTRODUCTION

10.1 The fallout of nuclear bomb debris considered in the preceding chapter may be described as being "local" in character. It consists chiefly of the larger particles which descend to earth, under the influence of gravity, in a matter of hours. The distances traveled are comparatively short and are not more than a few hundred miles from ground zero, in a downwind direction, even for the largest explosions. The early danger from the local fallout is due primarily to nuclear radiations from radioactive materials outside the body. During the first few days or weeks after the detonation, the radiation levels may be high enough to represent a danger to exposed persons. The radiation intensity decreases rapidly with time and, except for areas of very high initial contamination, it ceases to be a serious hazard within a few weeks. However, as seen earlier, the radioactivity diminishes more slowly as time passes, so that, even after several years, some will still persist.

10.2 There is another form of fallout that is much more widespread than the local type. It is that portion of the bomb residues which consists of very fine material that remains suspended in the air for times ranging from days to years. These fine particles can be carried over large areas by the wind and may, ultimately, be deposited in parts of the earth remote from the point of burst. The fallout of this fine debris is referred to as "world-wide fallout". It should not be inferred from this term, however, that none of the fine material is deposited in areas near the explosions, nor that such material is deposited uniformly over the earth. The nature of the distribution will be considered below; for the present, the main point is that the fallout under consideration is very much more widespread than the local type.

10.16 Genetic effects due to strontium-90 are relatively insignificant. In the first place, owing to their very short range in the body, the beta particles from this isotope in the skeleton do not penetrate to the reproductive organs. Further, the intensity of the secondary radiation (bremsstrahlung) produced by the beta particles is low. Finally, the amount of strontium-90 in soft tissue, from which the beta particles might reach the reproductive organs, is small and may be neglected in this regard.

Transfer of Strontium-90 from Soil to the Human Body

10.17 Since most of the strontium-90 is ultimately brought to earth by rain or snow, it will make its way into the soil and eventually into the human body through plants. At first thought, it might appear that the ratio of strontium to calcium in man would become similar to that in the soil from which he obtains his food. Fortunately, however, several processes in the chain of biological transfer of these elements from soil to the human body operate collectively to decrease the quantity of strontium-90 that is stored in man. These transfer processes include the following stages: (1) soil to plant, (2) plant to animal, and (3) animal to man. A certain proportion of calcium (and strontium) is obtained directly from plants, e. g., fruits and vegetables, but this is not very large, as will be seen shortly. Experiments show that in each of the three stages mentioned there is a natural discrimination in favor of calcium and against strontium, so that the ratio of strontium-90 to calcium in the human body is less than that in the top few inches of the soil.

10.18 Several factors make it difficult to generalize concerning the ratio of strontium-90 to calcium in the plant compared to that in the soil in which it grows. First, plants obtain most of their minerals through their root systems, but such systems vary from plant to plant, some having deep roots and others shallow roots. Most of the strontium-90 in undisturbed soil has been found close to the surface, so that the uptake of this isotope may be expected to vary with the growth habit of the plant. Second, although strontium and calcium, because of their chemical similarity, may be thought of as competing for entry into the root system of plants, not all of the calcium in soil is always available for assimilation. There are natural calcium compounds in soil which are insoluble and are not available as plant food until they have been converted to other compounds by agencies such as humic acid. Most of the strontium-90 in the present world-wide fallout, however, is in a water-soluble form. Third, although plants can sub-

stitute strontium for calcium, to some extent, it is apparent that they prefer calcium. Fourth, in addition to the strontium-90 which plants obtain from the soil, growing plants will also gather a certain amount of strontium-90 from fallout deposited directly on the surface of the plant. The experimental data at present available, however, indicate that the strontium-90/calcium ratio in plants is generally somewhat less than in the soil from which they were grown.

10.19 As the next link in the chain, animals consume plants as food, thereby introducing strontium-90 into their bodies. Once again, the evidence indicates that natural discrimination factors result in a strontium-90/calcium ratio in the edible animal products that is less than in the animal's feed. Very little strontium is retained in the soft tissue, so that the amount of strontium-90 in the edible parts of the animal is negligible. It is of particular interest, too, that the strontium-90/calcium ratio in cow's milk is also much lower than that in the cow's feed, since this is an important barrier to the consumption of strontium-90 by man. This barrier does not operate, of course, when plant food is consumed directly by human beings. However, it appears that about three-fourths of the calcium, and hence a large fraction of the strontium-90, in the average diet in the United States is obtained from milk and milk products. The situation may be different in areas where a greater or lesser dependence is placed upon milk and milk products in the diet.

10.20 Not all of the strontium-90 that enters the body in food is deposited in the human skeleton. An appreciable fraction of the strontium-90 is eliminated, just as is most of the daily intake of calcium. However, there is always some fresh deposition of calcium taking place in the skeletal structure of healthy individuals, so that strontium-90 is incorporated at the same time. The rate of deposition of both calcium and strontium-90 is, of course, greater in growing children than in adults.

10.21 In addition to the fact that the human metabolism discriminates against strontium, it will be noted that, in each link in the food chain, the amount of strontium-90 retained is somewhat less than in the previous link. Thus, a series of safeguards reduce deposition of strontium in human bone. A comparison, made in 1955, of the strontium-90/calcium ratio in the bones of children compared with the ratio in the soil gave a discrimination factor of about one-twelfth, that is to say, the strontium-90/calcium ratio in children's bones was found to be one-twelfth of the ratio in soil. Later measurements indicate that the proportion of strontium-90 getting into the bones may be considerably smaller than this.

STRONTIUM-90 ACTIVITY LEVELS

10.22 As there has been no experience with appreciable quantities of strontium-90 in the human body, the relationship between the probability of serious biological effect and the body burden of this isotope is not known with certainty, since it must be estimated indirectly. Such tentative estimates have been based on a comparison of the effects of strontium-90 with radium on experimental animals, and on the known effects of radium on human beings. From these comparisons it has been estimated that a body content of 10 microcuries (1 microcurie is a one-millionth part of a curie, as defined in § 9.118) of strontium-90 in a large proportion of the population would produce a noticeable increase in the occurrence of bone cancer. On this basis, the National Committee on Radiation Protection and the International Commission on Radiological Protection have suggested that, for individuals exposed to strontium-90 due to their occupation, the maximum permissible (or safe) amount of strontium-90 in the body should be 1 microcurie. Since the average amount of calcium in the skeleton of an adult human is about 1 kilogram, this corresponds to a concentration in the skeleton of 1 microcurie of strontium-90 per kilogram of calcium, i. e., one-tenth of the concentration which might be expected, on the average, to produce an observable effect above normal. For the population as a whole, the limit generally considered to be acceptable is 0.1 microcurie of strontium-90 per kilogram of calcium. This limit is in accord with the recommendations made in 1956 by the U. S. National Academy of Sciences.

10.23 As a result of nuclear test explosions in various countries during the past several years, there has been a small but steady gain in the strontium-90 content of the soil, plants, and the bones of animals. This increase is world-wide and is not restricted to areas in the vicinity of the test sites, although it is naturally somewhat higher in these regions because of the more localized fallout.[2] As the fine particles descend from the stratosphere, over a period of years, the gradual increase in the amount of strontium-90 may be expected to continue for some time, although there will be a certain amount of compensation due to natural decay.

[2] As stated in § 10.10, in the case of a surface or near-surface burst, an appreciable proportion of the strontium-90 formed will be found in the local fallout. It is then to be expected that areas near the explosion will be more highly contaminated in this isotope than are more distant regions, to an extent dependent upon such factors as the height (or depth) of burst, the total and fission yields of the explosion, and the prevailing atmospheric conditions. There is evidence that in the local fallout the strontium-90 constitutes a smaller percentage of the total fission products than it does farther away. This may be accounted for by the fact that the strontium-90 is not a direct fission product and so it is not formed at the instant of the explosion. It is produced gradually over a period of some minutes, as a result of two stages of radioactive decay starting with the gas krypton-90 which is formed in the fission process (see § 11.121).

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10.24 The quantities of strontium-90 that have accumulated so far in human beings are well below limits regarded as acceptable for the general population, and much less than those which might be expected to cause an observable increase in the frequency of bone tumors. Because the skeletons of very young children have developed under current fallout conditions, their content of strontium-90 provides the best indication of the maximum levels which might be expected to exist. As of January 1957, this was somewhat below one-thousandth (0.001) microcurie of strontium-90 per kilogram of calcium. Although there will be some increase toward a higher level, it is fairly certain, that if nuclear tests are carried out in the future at about the same rate as in the past, the long-term biological effects of strontium-90 will not be detectable. In the event that nuclear weapons with high fission yields were used extensively in warfare, calculations, based on somewhat uncertain premises, suggest that bomb debris from many thousands of megatons of fission would have to be added to the stratosphere before the worldwide fallout from these weapons would lead to a concentration of 1 microcurie of strontium-90 per kilogram of calcium in human beings.[3]

[3] A very thorough and comprehensive investigation of the strontium-90 hazard and of methods for combating it is being sponsored by the U. S. Atomic Energy Commission (Project Sunshine); for summary reports and references, see W. F. Libby, *Science, 123,* 657 (1956); *Proceedings of the National Academy of Sciences, 42,* 365, 945, (1956); J. L. Kulp, W. R. Eckelmann, and A. R. Schulert, *Science, 125,* 219 (1957).

burned or crushed to death. There were no cases of direct damage to internal organs by the blast among the survivors although there were some ruptured eardrums. The number was not large and was restricted almost entirely to persons who were within about 3,000 feet (0.6 mile) of ground zero.[1]

11.13 Many persons, who suffered no serious injury, reported temporary loss of consciousness. It was thought that this might be due to the direct action of blast, but it is possible that the effect resulted from violent displacement of the individuals by the air pressure wave.

11.14 From observations made with conventional high-explosive bombs, it appeared that peak overpressures of about 200 to 300 pounds per square inch would be necessary to cause death in human beings due to the direct effect of the blast and that perhaps 80 pounds per square inch would produce injury. However, these conclusions do not necessarily apply to the situation accompanying a nuclear explosion. In addition to the peak blast overpressure, the rate of rise of the pressure and the duration of the positive phase have an important influence.

11.15 When the pressure at the shock front increases rapidly or the positive phase lasts for an appreciable time (or both), serious blast injury (or death) can result at much lower peak pressures than would be the case for a slow rise or short duration of the overpressure. For example, tests indicate that a seven-fold increase in the duration of the blast wave results in a three-fold decrease in the overpressure associated with fatality in dogs. Since the duration of the positive phase of a nuclear blast wave is considerably longer than that for a conventional bomb explosion, it is to be expected that peak overpressures much less than 200 or 80 pounds per square inch will cause death or injury, respectively.

11.16 The general interaction of a human body with a blast wave is somewhat similar to that of a structure, as described in Chapter III. Because of the small size of the body, the diffraction process is quickly over and the body is rapidly engulfed and subjected to severe compression by the blast wave. This continues, with decreasing intensity, for the duration of the positive phase. At the same time the blast wind exerts a drag force of considerable magnitude.

11.17 Due to the compression and subsequent decompression, damage to the body occurs mainly at junctions between tissue and air-

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[1] The air blast overpressure required to cause rupture of eardrums appears to be highly dependent upon circumstances. Several observations indicate that the minimum overpressure is in the range from 10 to 15 pounds per square inch, but both lower and higher values have been reported.

containing organs, and at areas of union where bone and cartilaginous tissue join soft tissue. The chief consequences are as follows: damage to the central nervous system; heart failure due to direct disturbance of the heart; and suffocation caused by lung hemorrhage or liquid extrusion into the lung tissue. There may also be internal hemorrhage of the gastro-intestinal tract.

11.18 The drag (or wind) pressure can cause translational displacement of the body as a whole. The resulting injury (if any) will depend upon many circumstances; the most obvious of these are the speed at which the body moves, its acceleration and deceleration, the object it strikes, and the part of the body receiving the impact. The translational force, which determines the rate of movement, will be greatly influenced by the frontal surface of the body exposed to the blast wind. A person lying in a prone position, will, for example, be much less affected than one standing up.

Blast Injuries: Indirect

11.19 More important than the primary blast injuries in the nuclear attacks on Japan were the indirect or secondary effects due to collapsing buildings and to the great quantity and variety of the debris flung about by the air blast. Although a few persons were hurt by being hurled forcibly against solid objects, very many more were injured by flying objects and crushed or buried under buildings. Glass fragments in particular and, to a lesser extent, wood splinters and pieces of metal, penetrated up to an inch beneath the skin, occasionally through several layers of clothing. When the fragments were small, clothing provided some protection.

11.20 During the course of the Nevada tests in 1955, studies were made of the missiles produced inside houses and in the open behind the houses described in Chapter IV. Some of the results obtained, with special reference to the maximum density and velocity of the missiles, are given in Table 11.20. A fairly sharp missile, e. g., glass, with a velocity in the ranges quoted, can penetrate the abdominal wall of experimental animals. Most of the missiles collected inside the houses consisted of pieces of glass, while those outside were glass, pieces of masonry, rocks and sticks of wood. In locations shielded by houses or large pieces of machinery, the number of missiles was greatly reduced.

TABLE 11.20

DENSITY AND VELOCITY OF MISSILES

Peak overpressure (pounds per square inch)	*Maximum missile density (number per square foot)*	*Missile velocity (feet per second)*
5	66–207	60–340
3.8	17–66	60–280
1.9	0. 1–4	50–160

11.21 The nature of the indirect blast (or mechanical) injuries among the Japanese ranged from complete crushing, severe fractures, and serious lacerations with hemorrhage, to minor scratches, bruises, and contusions. Patients were treated for lacerations received out to 10,500 feet (2 miles) from ground zero in Hiroshima, and out to 12,000 feet (2.2 miles) in Nagasaki. These distances correspond roughly to those for significant damage to windows.

11.22 An interesting observation made among the Japanese survivors was the relatively low incidence of serious mechanical injuries. For example, among 675 patients there were no cases of fractures of the skull or back and only one fractured femur, although many such injuries must have undoubtedly occured. This was attributed to the fact that persons who suffered severe concussion or fracture or were rendered helpless by leg injuries, as well as those who were pinned beneath the wreckage, were trapped by the flames. Such individuals, of course, did not survive.

11.23 The type and degree of mechanical injuries, as well as their distribution among the types mentioned earlier, was found to depend very much on whether the persons were in the open or in a building at the time of the explosion. In general, mechanical injuries were less severe and less frequent among survivors in the open, where many died from other causes, as seen above. In buildings, the mechanical injuries were more serious, the extent of the injuries being dependent on the construction of the building, and, in particular, on the amount of glass.

11.24 Some reliable information concerning different types of mechanical injuries has been obtained from the study of a group of survivors at a military hospital in Hiroshima; the results are summarized in Table 11.24. In these cases, as in others, the incidence of fractures is low. In general, they may have represented only about 5 percent of the indirect blast injuries among survivors.

TABLE 11.24

TYPES OF MECHANICAL INJURIES AT HIROSHIMA

Injury	*Percentage*
Fracture	11
Laceration	35
Contusion	54

11.25 The healing of wounds was often slow, and accompanied by infection. There were several reasons for this situation. One was that mechanical injury was frequently accompanied by radiation injury which increased the susceptibility of the body to infection (see § 11.67). Another reason was the lack of proper treatment facilities, due to the large number of casualties and general disorganization following the nuclear explosions.

FLAME AND FLASH BURNS

11.26 As stated in Chapter VII, two general types of burns were experienced at Hiroshima and Nagasaki; these were (1) fire or flame burns, and (2) flash burns due to thermal radiation. The two types could usually be distinguished by the characteristic "profile" nature of flash burns, due to partial shielding, e. g., by clothing (§ 7.71). Flame burns, on the other hand, covered large parts of the body since the clothing usually caught fire. Where large parts of the body were exposed to thermal radiation, the flash burns were also of considerable area.

11.27 Among the survivors, the incidence of flame burns appeared to be very small. They constituted probably not more than 5 percent of the total burn injuries. This was the case because most of those who suffered flame burns did not survive, since they were caught in burning buildings and could not escape. The character of the flame burns after the nuclear bombings of Japan was similar to that of burns caused by other conflagrations, and so the subject need not be considered further here.

11.28 Flash burns, as indicated earlier, were very common at both Hiroshima and Nagasaki. In the former city, for example, some 40,000 fairly serious burn cases were reported. Apart from other injuries, the flash burns would have been fatal to nearly all persons in the open, without appreciable protection, at distances up to 6,000 feet (1.1 miles) or more from ground zero. Even as far out as 12,000 to 14,000 feet (2.2 to 2.6 miles), there were instances of thermal radiation burns which were bad enough to require treatment.

11.29 The frequency of flash burns was, of course, greatest among persons who were in the open. Nevertheless, there was a surprising number of such burns among individuals who were indoors. This was largely due to the fact that many windows, especially in commercial structures, were uncurtained or were wide open because of the summer weather. Hence, many persons inside buildings were directly exposed to thermal radiation. In addition to the protection afforded by clothing, particularly if light in color, as mentioned in Chapter VII (see Figs. 7.72 and 7.78), some shielding was provided by the natural promontories of the body, e. g., the nose, supraorbital (eye socket) ridges, and the chin.

11.30 In spite of the thousands of flash burns experienced after the nuclear attacks on Japan, only their general features were reported. However, this information has now been supplemented by observations made, especially on anesthetized pigs, both in the laboratory and at nuclear test explosions. The skin of white pigs has been found to respond to thermal radiation in a manner which is in many respects similar to, and can be correlated with, the response of human skin.

11.31 In addition to being chiefly restricted in area to exposed parts of the body, the majority of flash burns show a much smaller depth of penetration of the skin than do flame burns. This is to be expected if the thermal radiation effective in causing burns is emitted during a very short time. In the 20-kiloton explosions over Japan, for example, this was about 1 second. A very high temperature is thus produced near the surface of the skin in a small interval of time. As a result, some of the characteristics of flash burns, in addition to depth, differ from those of other, more familiar, burns. These differences may be less apparent if the thermal radiation is effective over a longer period of time, e. g., from an explosion of high energy yield.

11.32 The severity of the flash burns in Japan ranged from mild erythema (reddening) to charring of the outermost layers of the skin. Unlike low-temperature contact burns, there was no accompanying edema (accumulation of fluid) of the underlying tissue. Among those who were within about 6,000 feet (1.1 miles) from ground zero, the burn injuries were depigmented lesions (light in color), but at greater distances, from 6,000 to 12,000 feet (1.1 to 2.2 miles), the initial erythema was followed by the development of a walnut coloration of the skin, sometimes called the "mask of Hiroshima."

11.33 Burns of moderate second degree (and milder) usually healed within four weeks, but more severe burns frequently became

infected so that the healing process was much more prolonged. Even under the best conditions, it is difficult to prevent burns from becoming infected, and after the nuclear bombings of Japan the situation was aggravated by inadequate care, poor sanitation, and general lack of proper facilities. Nuclear radiation injury may have been a contributory factor in some cases due to the decrease in resistance of the body to infection.

11.34 Experimental flash burns have been obtained both in the laboratory and in nuclear tests which were apparently quite similar to those reported from Hiroshima and Nagasaki. In the more severe cases there was a central charred region with a white outer ring surrounded by an area of erythema. A definite demarcation both in extent and depth of the burns was noted, so that they were unlike contact burns which are generally variable in depth. The surface of the flash burns became dry without much edema or weeping of serum.

11.35 Another phenomenon which appeared in Japan after the healing of some of the more severe burns, was the formation of keloids, that is, thick overgrowths of scar tissue. It was suggested, at one time, that this might have been due to nuclear radiation, but such a view is no longer accepted. The degree of keloid formation was undoubtedly influenced by infections, that complicated healing of the burns, and by malnutrition. A secondary factor is the known disposition for keloid formation to occur among the Japanese, as a racial characteristic. Many spectacular keloids, for example, were formed after the healing of burns produced in the incendiary bomb attacks on Tokyo. It is of interest to note that a tendency has been observed for the keloids to disappear gradually in the course of time.

Effects of Thermal Radiation on the Eyes

11.36 The effects of thermal radiation on the eyes fall into two categories: these are (1) retinal burns, and (2) flash blindness. Retinal burns can result from the concentration of sufficient direct thermal energy on the retina of the eye. Because of the focusing action of the lens, enough energy can be collected to produce a burn on the retina at such a distance from the explosion that the thermal radiation intensity is too small to produce a skin burn. As a result of accidental exposures at nuclear tests, a few retinal burns have been experienced at a distance of 10 miles from an explosion of approximately 20 kilotons energy yield. It is believed that under suitable conditions, such burns might result even farther away.

11.37 Much of the thermal radiation responsible for flash burns arrives so soon after the explosion that reflex actions, such as blinking and contraction of the eye pupil, give only limited protection. At night, when the eye is dark-adapted and the pupil is large, retinal burns could occur at greater distances from the nuclear explosion than in daylight. In all instances, there will be temporary loss of visual acuity, at least, but the ultimate effect will depend upon the severity of the burn and, to a greater extent, upon its location. If the burn is mild, or on the periphery of the visual field, the acuity may hardly be effected, but in more serious cases there may be considerable loss of vision.

11.38 There is a possibility that small permanent blind spots may be produced on the retinas of persons who focus their eyes directly on the fireball, so that the image of the fireball is formed in the region of central vision. The chance that an individual will be looking directly at the ball of fire is small, particularly for low-yield nuclear weapons which have a short period in which the rate of thermal radiation emission is high. Temporary "flash blindness" or "dazzle," due to the flooding of the eye with the brilliant light scattered from the sky, ground, and other surroundings, is much more probable. This is a temporary embarrassment, however, and vision is usually regained within a short time.

11.39 It is an interesting fact that among the survivors in Hiroshima and Nagasaki, eye injuries directly attributable to thermal radiation appeared to be relatively unimportant. There were many cases of temporary blindness, occasionally lasting up to 2 or 3 hours, but more severe eye injuries were not common.

11.40 The eye injury known as keratitis (an inflammation of the cornea) occurred in some instances. The symptoms, including pain caused by light, foreign-body sensation, lachrymation, and redness, lasted for periods ranging from a few hours to several days. Among 1,000 cases, chosen at random, of individuals who were in the open, within some 6,600 feet (1.25 miles) of ground zero at the time of the explosions, only 42 gave a history of keratitis coming on within the first day. Delayed keratitis was reported in 14 additional cases, with symptoms appearing at various times up to a month or more after the explosion. It is possible that nuclear radiation injury, which is associated with delayed symptoms, as will be seen below, may have been a factor in these patients.

11.41 Investigators have reported that in no case, among the 1,000 examined, was the thermal radiation exposure of the eyes apparently

sufficient to produce permanent opacity of the cornea. This observation is surprising in view of the severe burns of the face suffered by many of the patients. Thus, in approximately one-quarter of the cases studied there had been facial skin burns and often burning of the eyebrows and eyelashes. Nevertheless, some three years later the corneas were normal. No persons in the survey group developed permanent central scotomata (blind spots), although several stated that they were looking in the direction of the bomb at the time of the explosion.

11.42 Several reasons have been suggested for the scarcity of severe eye injuries in Japan. For example, it seems probable that the blink reflex was rapid enough to provide significant protection. Another possible explanation is that the recessed position of the eyes and, in particular, the overhanging upper lids served to decrease the direct exposure to thermal radiation. On the basis of probability, only a small proportion of individuals would actually be facing the explosion and owing to the bright sunlight the pupils of the eyes would be small, thus decreasing the exposed area.

Nuclear Radiation Injury

11.43 The injurious effects of nuclear radiation from a nuclear bomb represent a phenomenon which is completely absent from conventional explosions. For this reason the subject of radiation injury (or sickness) will be described at some length here. It should be understood, however, that the extended discussion is not necessarily meant to imply that nuclear radiation would be the most important source of casualties in a nuclear explosion. This was certainly not the case in Japan, as indicated earlier, where the bombs were detonated at a height of approximately 1,850 feet above the ground. Such injuries as were caused by nuclear radiation were due to the initial radiation. The effect of the residual nuclear radiation, in the form of fallout, was negligible. However, as was seen in Chapter IX, the situation could be very different in the event of a surface burst of a fission weapon.

11.44 It has long been known that excessive exposure to nuclear (or similar) radiations, such as X-rays, alpha and beta particles, gamma rays, and neutrons, which are capable of producing ionization, either directly or indirectly (§ 8.22), can cause injury to living organisms. After the discovery of X-rays and radioactivity, toward the end of the nineteenth century, serious and sometimes fatal exposure to radiation was sustained by radiologists before the dangers were

realized. In the course of time, however, recommendations for preventing overexposures were adopted and radiation injuries became less frequent. Nevertheless, occasional overexposures have occurred among personnel operating radiographic equipment, powerful X-ray machines in industrial laboratories, cyclotrons, and nuclear reactors, or working with radioactive or fissionable materials.

11.45 The harmful effects of radiation appear to be due to the ionization (and excitation) produced in the cells composing living tissue. As a result of ionization, some of the constituents, which are essential to their normal functioning, are damaged or destroyed. In addition, the products formed may act as cell poisons. Among the observed consequences of the action of nuclear (or ionizing) radiations on cells is breaking of the chromosomes, swelling of the nucleus and of the entire cell, destruction of cells, increase in viscosity of the cell fluid, and increased permeability of the cell membrane. In addition, the process of cell division (or "mitosis") is delayed by exposure to radiation. Frequently, the cells are unable to undergo mitosis, so that the normal cell replacement occurring in the living organism is inhibited.

11.46 Before the bombings of Hiroshima and Nagasaki, radiation injury was a rare occurrence and relatively little was known of the phenomena associated with radiation sickness. In Japan, however, a large number of individuals were exposed to doses of radiation ranging from insignificant quantities to amounts which proved fatal. The effects were often complicated by other injuries and shock, so that the symptoms of radiation sickness could not always be isolated. Further, the great number of patients and the lack of facilities after the explosions made it impossible to make detailed observations and keep accurate records. Nevertheless, certain important conclusions have been drawn from Japanese experience with regard to the effects of nuclear radiation on the human organism.

11.47 Since 1945, further information on this subject has been gathered from other sources. These include animal experiments and a few laboratory accidents, involving about a dozen or so human beings. The most detailed knowledge, however, was obtained from a careful study of over 250 persons in the Marshall Islands, who were accidentally exposed to nuclear radiation from fallout following the test explosion on March 1, 1954 (§ 9.86). The exposed individuals included both Marshallese and a small group of American servicemen. The whole-body radiation doses ranged from relatively small values (14 roentgens), which produced no symptoms, to amounts (175

roentgens) somewhat less than would be expected to result in fatality to a few percent of those exposed.

11.48 It has been established that all radiations capable of producing ionization (or excitation) directly, e. g., alpha and beta particles, or indirectly, e.g., X-rays, gamma rays, and neutrons, can cause radiation injury of the same general type. However, although the effects are qualitatively similar, the various radiations differ in the depth to which they penetrate the body and in the degree of injury corresponding to a specified amount of energy absorption. As stated in § 8.31, this difference is (partly) expressed by means of the relative biological effectiveness (or RBE).

11.49 For beta particles, the RBE is close to unity; this means that for the same amount of energy absorbed in living tissue, beta particles produce about the same extent of injury within the body as do X-rays or gamma rays.[2] The RBE for alpha particles from radioactive sources has been variously reported to be from 10 to 20, but this is believed to be too large in most cases of interest. For nuclear bomb neutrons, the RBE for acute radiation injury has been taken as 1.7 (§ 8.69), but it is appreciably larger where the formation of opacities of the lens of the eye (cataracts) are concerned. In other words, neutrons are much more effective than other nuclear radiations in causing cataracts.

General Radiation Effects

11.50 The effects of nuclear radiations on living organisms depend not only on the total dose, that is, on the amount absorbed, but also on the rate of absorption, i. e., on whether it is acute or chronic, and on the region and extent of the body exposed (§ 9.38). A few radiation phenomena, such as genetic effects (see § 11.124, *et seq.*), apparently depend only upon the total dose received and are independent of the rate of delivery. In other words, the injury caused by radiation to the germ cells is cumulative. In the majority of instances, however, the biological effect of a given total dose of radiation decreases as the rate of exposure decreases. Thus, to cite an extreme case, 700 roentgens in a single dose would be fatal, if the whole body were exposed, but it would not cause death or have any noticeable external effects if supplied more or less evenly over a period of 30 years.

11.51 A skin exposure dose of 700 roentgens of X-rays will cause a certain degree of erythema (reddening) if administered locally to

[2] Beta particles from sources on or near the body can also cause skin burns (see § 11.94).

a small area over a period of 1 hour. However, to produce the same apparent effect with two shorter treatments separated by an interval of 24 hours, each dose must be about 535 roentgens, so that a total of 1,070 roentgens is required. If the exposure is spread over a period of 1 month, the total dose may approach 2,000 roentgens in order to cause the same degree of erythema. The explanation of these results is that in the skin new cells are continually being produced at a rapid rate in order to take care of normal wear and tear. Hence, the majority of cells damaged (or killed) by radiation are replaced by new cells and there is a certain amount of natural recovery between successive doses.

11.52 Although in most cases the rate of formation of new cells is not as great as it is in the skin, the ability to recover, to some extent, from the effects of radiation appears to be possessed by many body tissues. The rate of replacement of mature cells of blood-forming tissues and of the lining of the gastro-intestinal tract, as well as of sperm cells, is also very great.

11.53 It was seen in Chapter IX that the human body is able to withstand continual exposure to small doses of radiation from natural sources without any obviously harmful consequences. The probable reason, as implied above, is that most of the cells damaged by the radiation are replaced by new ones. But if the rate of delivery of the radiation is high or the total dose received in a relatively short time is large, recovery cannot keep pace with the damage, and injury results.

11.54 Whether the injury due to nuclear radiation is reparable or not, appears to depend to a large extent on the natural capability of the affected organ (or organ system) to repair itself as a result of damage of any kind. Thus, radiation injury to brain and kidney is largely irreparable, but damage to bone marrow, the gastro-intestinal tract, and skin, on the other hand, is to a great extent reparable.

11.55 It has already been indicated that the injury caused by a certain dose of radiation will depend upon the extent and part of the body that is exposed. For example, an acute exposure dose of 700 roentgens applied to a small region may result in considerable biological damage to the irradiated area, but the over-all health of the individual may be apparently unaffected. If the whole body receives the dose of 700 roentgens, however, death will probably result. One reason for this difference is that when the exposure is restricted, the unexposed regions can contribute to the recovery of the injured area. But if the whole body is exposed, many organs are affected and recovery is much more difficult.

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11.56 Different portions of the body show different sensitivities to radiation, although there are undoubtedly variations of degree among individuals, as will be seen below. In general, the most radiosensitive parts include the lymphoid tissue, bone marrow, spleen, organs of reproduction, and gastro-intestinal tract. Of intermediate sensitivity are the skin, lungs, kidney, and liver, whereas muscle and full-grown bones are the least sensitive.

Effects of Acute Radiation Doses

11.57 In the present section there will be described some of the more obvious effects of an acute dose of radiation received over the whole body. Such a situation could result from exposure of persons to the initial nuclear radiation from a nuclear explosion. The results given in Table 11.57, which apply to man, are based upon experiments with animals, as well as upon the conclusions drawn from observations made in Japan and of the individuals exposed on the Marshall Islands. The percentage of fatalities corresponding to any particular dose may be decreased to some extent by treatment without delay. The data in Table 11.57 are also plotted in Fig. 11.57; the two curves show the

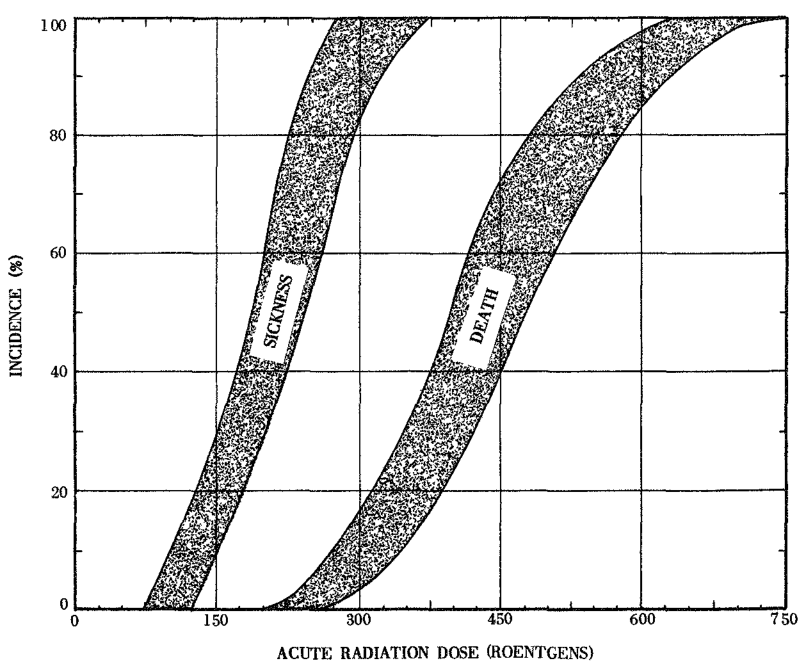

Figure 11.57. Incidence of sickness and death due to acute exposure to various doses of nuclear radiation.

expected percentage incidence of radiation sickness and of subsequent deaths within 30 days (or so), respectively, for various acute radiation doses over the whole body.

TABLE 11.57

EXPECTED EFFECTS OF ACUTE WHOLE-BODY RADIATION DOSES

Acute dose (roentgens)	*Probable effect*
0 to 50	No obvious effect, except possibly minor blood changes.
80 to 120	Vomiting and nausea for about 1 day in 5 to 10 percent of exposed personnel. Fatigue but no serious disability.
130 to 170	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 percent of personnel. No deaths anticipated.
180 to 220	Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 50 percent of personnel. No deaths anticipated.
270 to 330	Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20 percent deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months.
400 to 500	Vomiting and nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50 percent deaths within 1 month; survivors convalescent for about 6 months.
550 to 750	Vomiting and nausea in all personnel within 4 hours from exposure, followed by other symptoms of radiation sickness. Up to 100 percent deaths; few survivors convalescent for about 6 months.
1000	Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness.
5000	Incapacitation almost immediately. All personnel will be fatalities within 1 week.

11.58 It will be noted that, both in Table 11.57 and in Fig. 11.57, a particular effect (or incidence) is associated with a range of exposure doses in roentgens. The reason for this uncertainty is that there are many factors, some known and some unknown, which determine the effect on the body of a specified radiation exposure dose. In addition to biological variations among individuals, which will be referred to shortly, there are such considerations as the ages of the exposed persons and their state of health, depth of penetration into the body and the organs absorbing the radiation, and the orientation of the body with reference to the source of the radiation, leading to possible shielding of one part of the body by another. These and other factors will influence the consequence of exposure to a specified dose in roentgens.

11.59 The differences in response to radiation by individuals is brought out by the fact that not all members of a group of human

beings, assumed to be irradiated with the same dose under the same conditions, react in the same manner. For example, only 20 percent of those exposed would be expected to succumb to an acute dose in the vicinity of 300 roentgens. The other 80 percent will suffer from radiation sickness but will probably recover. The difference in the effect of the radiation on different individuals is attributed to what is called "biological variability." It is not a unique characteristic of nuclear radiation effects, since it occurs when other physiological stimuli are involved. The existence of this natural variability factor thus makes it necessary to deal with the average behavior of a large number of persons. It is impossible to predict how a given individual will respond to a specified dose of radiation, although the expected average effect on a large group may be known, provided the conditions are precisely defined.

11.60 As a point of reference, in considering the biological effects of acute radiation doses over the whole body, a quantity called the "median lethal dose" is commonly used.[3] It is the whole-body dose which is expected to result in the death within about a month (or so) of 50 percent of exposed individuals among a large group. The other 50 percent will be sick but will probably recover within 6 months. Bearing in mind the uncertainties, referred to above, in stating a precise value, it is generally accepted at the present time that the median lethal dose is an exposure of 450 roentgens. This may, however, be subject to change as more information on the effects of acute radiation on man becomes available.

11.61 It appears from recent studies, both in the laboratory and in the field, that there is probably no single value for the median lethal dose that applies under all conditions. For example, it was concluded, from observations on the blood changes among the individuals accidentally exposed to fallout radiation on the Marshall Islands (see § 11.73), that the median lethal dose would have been somewhat less than 450 roentgens. On the other hand, an examination of the data obtained from Japan indicates a higher value for the median lethal dose for exposure to the initial nuclear radiation. Although both values are subject to considerable errors, it is possible that the difference arises from the fact that the fallout material was spread over a large area, so that the radiation reached the exposed individuals from many directions. With the initial radiation, however, the exposure was essentially from one direction only, so that some parts of the body were shielded by others. A given radiation

[3] The median lethal dose is frequently abbreviated as MLD, LD/50, or LD_{50}.

exposure in roentgens would then cause more damage in the former case, leading to a lower value for the median lethal dose. For the present purpose, the value of 450 roentgens will be adopted as a reasonable average.

CHARACTERISTICS OF ACUTE RADIATION INJURY

Large Dose (Over 700 Roentgens): Survival Improbable

11.62 Very large doses of whole-body radiation, e. g., 5,000 roentgens or more, result in very rapid injury to the central nervous system. The symptoms are hyperexcitability, ataxia (lack of muscular coordination), respiratory distress, and intermittent stupor. There is almost immediate incapacitation, and death is certain in a few hours to a week or so after the acute exposure. If the dose is in the range of about 700 to 1,000 roentgens, roughly, it is the gastro-intestinal system which exhibits the earliest severe clinical effects in the form of nausea and vomiting within the first 3 or 4 hours. The larger the dose the sooner are these symptoms experienced. They are then followed, in more or less rapid succession, by prostration, diarrhea, anorexia (lack of appetite and dislike for food), and fever. As observed after the nuclear attacks on Japan, the diarrhea was frequent and severe in character, being watery at first and tending to become bloody later.

11.63 The sooner the foregoing symptoms of radiation injury develop, the sooner is death likely to result. Although there is no pain during the first few days, patients experience feelings of discomfort or uneasiness (malaise), accompanied by marked depression and bodily fatigue. In some of the cases receiving a lower dose, the early stages of the severe radiation sickness are followed by a so-called "latent" period of 2 or 3 days (or more), during which the patient appears to be free from symptoms, although profound changes are taking place in the body, especially in the blood-forming tissues. This period, when it occurs, is followed by a recurrence of the early symptoms, often accompanied by delirium or coma, terminating in death usually within 2 weeks.

11.64 Other symptoms which have been observed are secondary infection and a tendency to spontaneous internal bleeding toward the end of the first week. At the same time, swelling and inflammation of the throat is not uncommon. Loss of hair (epilation), mainly from the head, will usually occur by the end of the second week. The de-

velopment of severe radiation sickness among the Japanese was accompanied by an increase in the body temperature. Generally there was a step-like rise between the fifth and seventh days, sometimes as early as the third day, after exposure, usually continuing until the day of death. There were also striking changes in the blood of the patient, to which reference will be made shortly (§ 11.73). Examination after death revealed a decrease in size and degenerative changes in testes and ovaries. Ulceration of the tonsils and of the mucous membrane of the large intestine was also noted in some cases.

Dose of 300 to 500 Roentgens: Survival Possible

11.65 In the dose range from about 300 to 500 roentgens, from which survival is possible but by no means certain, the initial symptoms are similar to those following a somewhat larger dose, namely, nausea, vomiting, diarrhea, loss of appetite, and malaise. However, these symptoms will develop later, although generally during the day of the exposure, and be less severe. After the first day or two the symptoms disappear and there may be a latent period of several days up to two weeks during which the patient feels relatively well, although important changes are occurring in the blood. Subsequently, there is a return of the symptoms, including fever, diarrhea, and the step-like rise in temperature referred to above.

11.66 Commencing about 2 or 3 weeks after exposure, there is a marked tendency to bleed (hemorrhage) into various organs, and hemorrhages under the skin (petechiae) are observed. Particularly common are spontaneous bleeding in the mouth and from the lining of the intestinal tract. There may be blood in the urine from bleeding into the kidney or into the urinary tract leading from the kidney. The hemorrhagic tendency depends mainly upon depletion of certain components of the blood, resulting in defects in the complex blood-clotting mechanism (see § 11.79). Loss of hair, which is very characteristic of radiation exposure, also starts after about 2 weeks, that is, immediately following the latent period.

11.67 Susceptibility to infection of wounds, burns, and other lesions, is a serious complicating factor. This results to a large degree from the loss of white blood cells, and a marked depression in the body's normal immunological mechanism. For example, ulceration about the lips commences after the latent period and spreads from the mouth through the entire gastro-intestinal tract in the terminal stage of the sickness. The multiplication of bacteria, made possible by the decrease of the white cells of the blood, thus allows an overwhelming infection to develop.

11.68 In the more serious cases in Japan, who had received a fairly large dose of radiation, there was severe emaciation with fever and delirium, followed by death within 2 to 12 weeks after exposure. Those patients who survived for 3 to 4 months, and did not succumb to tuberculosis, lung diseases, or other complications, gradually recovered. There was no evidence of permanent loss of hair, and examination of 824 survivors some 3 to 4 years later showed that their blood composition was not significantly different from that of a control group in a city not subjected to nuclear attack. The incidence of long-term effects, such as cataracts and leukemia, will be considered below.

Doses of 100 to 250 Roentgens: Survival Probable

11.69 Exposure of the whole body to a radiation dose in the range of approximately 100 to 250 roentgens will result in a certain amount of sickness, but it will probably not prove fatal. Doses of this magnitude were common in Hiroshima and Nagasaki, particularly among persons who were at some distance from the nuclear explosion. Of the 250 individuals accidentally exposed to fallout in the Marshall Islands following the test explosion of March 1, 1954, a group of 64 received radiation doses in this range. It should be pointed out that the exposure of the Marshallese was not strictly of the acute type, as arbitrarily defined in § 9.38, since it extended over a period of some 45 hours. More than half the dose, however, was received within 24 hours and the observed effects were undoubtedly similar to those to be expected from an acute exposure of the same amount.

11.70 The sickness resulting from radiation doses in the range from 100 to 250 roentgens presents much the same general picture as in the case of more severe exposure, except that the onset is less abrupt and the symptoms are less marked. There is usually some nausea, vomiting, and diarrhea on the first day or so following irradiation, but subsequently there is a latent period, up to 2 weeks or more, during which the patient has no disabling illness and can proceed with his regular occupation. The usual symptoms, such as loss of appetite, malaise, loss of hair, diarrhea, and tendency to bleed then appear, but they are not very severe (Fig. 11.70). The changes in the character of the blood, which accompany radiation injury, become significant during the latent period and persist for some time. If there are no complications, due to other injuries or to infections, there will be recovery in nearly all cases, with hair growth recommencing after about 2 months. In general, the more severe the early stages of the radiation sickness, the longer and more difficult will be the

Figure 11 70. Loss of hair in child exposed to approximately 175 roentgens of gamma radiation.

process of recovery. Adequate care and the use of antibiotics, as may be indicated clinically, can greatly expedite complete recovery of the more serious cases.

Small Doses: Minor Injury

11.71 Single exposures of from 25 to 100 roentgens over the whole body may produce mild and somewhat indefinite symptoms, or there may be nothing other than the blood changes which have been observed, to a minor extent, following doses as small as 14 roentgens. Disabling sickness is not common, and exposed individuals should be able to proceed with their usual duties.

Summary of Clinical Symptoms of Radiation Sickness

11.72 The most obvious and earliest symptoms of radiation sickness are nausea, vomiting, and diarrhea. The appearance, severity, and duration of these symptoms bear a direct relationship to the degree

of exposure and an inverse relationship to the probability of recovery. The occurrence and length of the latent period which follows the initial symptoms, and the subsequent effects, are also related to these factors. A simplified summary of the clinical symptoms (or syndrome) of radiation sickness of three degrees of severity are given in Table 11.72. It should be understood that the time scale is approximate and that the order of appearance of the various symptoms after the latent period, as well as the symptoms themselves, may vary from one individual to another.

TABLE 11.72

SUMMARY OF CLINICAL SYMPTOMS OF RADIATION SICKNESS

Time after exposure	Survival improbable (700 r or more)	Survival possible (550 r to 300 r)	Survival probable (250 r to 100 r)
	Nausea, vomiting, and diarrhea in first few hours.	Nausea, vomiting, and diarrhea in first few hours.	Possibly nausea, vomiting, and diarrhea on first day.
1st week	No definite symptoms in some cases (latent period).	No definite symptoms (latent period).	No definite symptoms (latent period).
	Diarrhea Hemorrhage Purpura Inflammation of mouth and throat. Fever		
2nd week	Rapid emaciation Death (Mortality probably 100 percent).	Epilation Loss of appetite and general malaise. Fever	
3rd week		Hemorrhage Purpura Petechiae Nosebleeds Pallor Inflammation of mouth and throat. Diarrhea Emaciation	Epilation Loss of appetite and malaise Sore throat Hemorrhage Purpura Petechiae Pallor Diarrhea Moderate emaciation.
4th week			
		Death in most serious cases. (Mortality 50 percent for 450 roentgens.)	Recovery likely in about 3 months unless complicated by poor previous health or superimposed injuries or infections.

Effects of Radiation on Blood Constituents

11.73 Among the biological consequences of exposure of the whole body to a single dose of nuclear radiation, perhaps the most striking and characteristic are the changes which take place in the blood. These changes have been observed, to a small extent, among a group of individuals with doses as low as 14 roentgens, but they become more marked with increasing dosage. Much information on the hematological response of human beings to nuclear radiation was obtained after the nuclear explosions in Japan and also from observations on victims of laboratory accidents. The situation which developed in the Marshall Islands in March 1954, however, provided the opportunity for a very thorough study of the effects of small and moderately large doses of radiation, up to 175 roentgens, on the blood of human beings. The descriptions given below, which are in general agreement with the results observed in Japan, are based largely on this study.

11.74 One of the most striking hematological (blood) changes associated with radiation injury is that in the leukocyte (white blood cell) content. The leukocytes are those cells concerned with resisting bacterial invasion of the body. Their numbers in the blood are observed to increase rapidly during the course of an infection, as they are required to combat the invading organisms. The loss of this ability to meet the bacterial invasion, whether due to radiation or any other injury, is a very grave matter, and bacteria which are normally held in check by the leukocytes can then multiply rapidly, causing serious consequences. There are several types of leukocytes with different specialized functions, but which have in common the general property of resisting infection or removing toxic products from the body, or both. Leukocytes are named according to their appearance, e. g., granulocytes, to their origin, e. g., lymphocytes, or to their acid-base affinities, e. g., acidophiles, neutrophiles, and basophiles.

11.75 After the body has been exposed to radiation in the sublethal range, i. e., about 250 roentgens or less, the total number of leukocytes increases sharply during the first two days or so, and then decreases below normal levels. The white blood cell count fluctuates over the next 5 or 6 weeks, with no definite minimum. In the course of this fluctuation the count may possibly rise above normal on occasions. During the seventh or eighth weeks the white count becomes stabilized at low levels, and a minimum probably occurs at about this time. An upward trend is observed in succeeding weeks, but complete recovery may require several months or more.

11.76 The neutrophiles, which defend the body against invading bacteria, are chiefly formed in the bone marrow. The neutrophile count parallels the total white blood cell count, so that the initial increase observed in the latter is apparently due to the increase in the mobilization of neutrophiles. Complete return of the number of neutrophiles to normal does not occur for several months.

11.77 In contrast to the behavior of the neutrophiles, the number of lymphocytes, produced in parts of the lymphatic tissues of the body, e. g., lymph nodes and spleen, shows a sharp drop soon after exposure to radiation. It continues to remain considerably below the normal value for several months and recovery may require many months or even years. However, to judge from the observations made in Japan, the lymphocyte count of exposed individuals 3 or 4 years after exposure was not significantly different from that of unexposed persons.

11.78 As seen above, the function of the white blood cells is to defend the body against infection and to remove toxic products. The failure of the bone marrow and of the lymphoid tissues to produce granulocytes and lymphocytes, respectively, as a result of the action of radiation, means that an important defense mechanism of the body is rendered largely inoperative. This accounts in part for the increased susceptibility to infection, mentioned earlier, which accompanies radiation sickness. Other contributory factors are deficiencies in the ability to produce antibodies and defective functioning of the remaining lymphocytes.

11.79 A further significant hematological effect is that in the platelets, a constituent of the blood which plays an important part in connection with blood clotting. Unlike the fluctuating total white count, the number of platelets falls steadily and, for a sublethal dose, reaches a minimum at the end of about a month. For higher radiation doses the platelet count falls off more rapidly and attains a lower minimum in a shorter time. The decrease in the number of platelets is followed by a partial recovery, but a normal count may not be attained for several months or even years after exposure. It is the decrease in the platelet content which partly explains the appearance of hemorrhage and purpura as a result of radiation injury.

11.80 The erythrocyte (red blood cell) count also undergoes a decrease as a result of radiation exposure, so that symptoms of anemia, e. g., pallor, become apparent. However, the change in the number of erythrocytes is much less striking than that in the white blood cells and platelets, especially for exposures in the range of 200 to 400 roentgens. Whereas the response in these cells is rapid, the red cell count shows little or no change for several days. Subsequently, there is a

decrease which may continue for 2 or 3 weeks, but this is followed by a gradual increase in those who survive.

11.81 As an index of severity of radiation exposure, particularly in the sublethal range, the total white cell or neutrophile counts are of limited usefulness because of the wide fluctuations and also because several weeks may elapse before the maximum depression is observed. The lymphocyte count is of more value in this respect, particularly in the low dose range, since depression occurs within a few hours of exposure. However, a marked decrease in the number of lymphocytes occurs even with low doses and there is relatively little difference with larger doses. Consequently, the white cell count is not very useful as an index of exposure at the higher dose levels.

11.82 The platelet count, on the other hand, appears to exhibit a regular pattern, with the maximum depression being attained at approximately the same time for various exposures in the sublethal range. Further, in this range, the degree of depression from the normal value is roughly proportional to the estimated dose. It has been suggested, therefore, that the platelet count might serve as a convenient and relatively simple direct method for determining the severity of radiation injury in the sublethal range. The main disadvantage is that an appreciable decrease in the platelet count is not apparent until some time after the exposure.

LATE EFFECTS OF NUCLEAR RADIATION

Cataracts

11.83 There are a number of consequences of nuclear radiation which may not appear for some years after exposure. Among them, apart from genetic effects, are the formation of cataracts, leukemia, and retarded development of children *in utero* at the time of the exposure. Information concerning these late effects have been obtained from continued studies in Japan made chiefly under the direction of the Atomic Bomb Casualty Commission.[4]

11.84 An examination for the incidence of cataracts among the survivors of the bombings of Hiroshima and Nagasaki has revealed well over 100 cases of non-vision-disturbing lens opacities in persons who were within about 3,000 feet (0.6 mile) from ground zero at the times of the respective explosions. In a small proportion only of the

[4] The Atomic Bomb Casualty Commission of the U. S. National Research Council is sponsored by the Atomic Energy Commission. One of its purposes is to study the long-term effects of exposure to nuclear radiation.

patients was the opacity serious enough to require an operation. The cataracts are similar to those which have been previously associated with overexposure to X-rays or gamma rays, and so they are probably due to the initial nuclear radiation from the nuclear bombs. Because of the high biological effectiveness of fast neutrons for the formation of lens opacities (§ 11.49), it is probable that this radiation was largely responsible for the Japanese cases.

11.85 Most persons in the same zone, with respect to the center of the explosion, died either from thermal or mechanical injuries or from radiation sickness. Consequently, it is probable that all (or nearly all) the survivors who later developed cataracts must have received at least moderate doses of radiation. This view is supported by the fact that essentially all these individuals suffered complete (but transient) epilation and many exhibited other characteristic clinical symptoms of radiation sickness.

Leukemia

11.86 A review of mortality rates has shown that, as a cause of death, leukemia, a disease associated with an overproduction of white blood cells, is much more common among radiologists than among other physicians. It has therefore been accepted that chronic exposure to moderate doses of nuclear radiation is conducive to leukemia. It now appears from a study of the survivors of the nuclear explosions over Japan, that the disease may result from a large single (acute) dose of radiation. The first definite evidence of an increase in the incidence of leukemia among the inhabitants of Hiroshima and Nagasaki was obtained in 1947. At least 2 years elapsed, therefore, between exposure and the development of the symptoms. The number of new cases reported has increased fairly regularly in succeeding years.

11.87 Essentially all of the cases of leukemia, which could be attributed to radiation because of other symptoms, e. g., epilation, occurred among individuals who were within about 4,600 feet (0.9 mile) of ground zero. In this region, the minimum radiation dose, probably received over an extensive part of the body, must have approached the median lethal value of 450 roentgens. A survey of a large number of these patients showed that the incidence of leukemia among the survivors was, on the average, about one in 500 compared with one in 50,000 among the general (unexposed) population of Japan.

Retarded Development of Children

11.88 Among the mothers who were pregnant at the times of the nuclear explosions in Japan, and who received sufficiently large doses to show the usual radiation symptoms, there was a marked increase over normal in the number of still-births and in the deaths of newly born and infant children. A study of the surviving children made 4 or 5 years later has shown a slightly increased frequency of mental retardation. However, nearly all the mothers of these children, then *in utero*, were so close to ground zero that they must have been exposed to at least 450 roentgens of nuclear radiation. Maldevelopment of the teeth, attributed to injury of the roots, was also noted in many of the children.

11.89 A comparison made about 1952 of exposed children, whose ages ranged from less than 1 to about 14 years at the time of the explosions, with unexposed children of the same age, showed that the former had somewhat lower average body weight and were less advanced in stature and sexual maturity. On the other hand, no significant differences were observed in various neuromuscular coordination and muscular tests.

11.90 In connection with the subject of the development of children, it should be mentioned that those who were conceived in Japan after the nuclear attacks, even by irradiated parents, appear to be quite normal. The fear expressed at one time that there would be a sharp increase in the frequency of abnormalities has not been substantiated (see, however, § 11.124).

Effect of Radiation on Other Injuries

11.91 The superposition of radiation injury upon injuries from other causes may be expected to result in an increase in the number of cases of shock. For example, the combination of sublethal exposure and moderate thermal burns will produce earlier and more severe shock than would the comparable burns alone. The healing of wounds of all kinds will be retarded because of the susceptibility to secondary infection accompanying radiation injury and for other reasons. In fact, infections, which could normally be dealt with by the body, may prove fatal in such cases.

RESIDUAL RADIATION HAZARDS

Gamma Radiation

11.92 The biological effects of the residual nuclear radiation are, in general, similar to those of the initial radiation, but there are certain aspects, arising from the nature of the fission products and fallout, that require special consideration. The topics to be discussed here are (1) the residual gamma radiation, (2) beta-particle emitters, and (3) internal sources of radiation.

11.93 Although the gamma rays from fission products have a lower energy and are somewhat less penetrating than those present in the initial nuclear radiation, their biological effects are similar. However, as indicated in § 11.61, a certain number of roentgens of residual gamma radiation from fallout may produce greater biological injury than that number of roentgens of initial gamma radiation. In the latter case, when most of the radiation comes from one direction, namely, that of the exploding bomb, there may be partial shielding of one portion of the body by another. Radiation from fallout, on the other hand, can reach the body from many directions and there is very little self-shielding. The fact that the residual radiation is spread over a longer period than the initial radiation is not of great significance, because most of the dose from fallout will generally be received during the first day or two following the nuclear explosion. The normal recovery in this time is not large, so that the dose may be treated essentially as acute.

Beta-Particle Emitters

11.94 Injury to the body from external sources of beta particles can arise in two general ways. If the beta-particle emitters, e. g., fission products in the fallout, come into actual contact with the skin and remain for an appreciable time, a form of radiation damage, sometimes referred to as "beta burn," will result. In addition, in an area of extensive fallout, the whole surface of the body will be exposed to beta particles coming from many directions. It is true that clothing will attenuate this radiation to a considerable extent; nevertheless, the outer layers of the skin could receive a large dose of beta particles. In some circumstances this might cause serious burns.

11.95 Valuable information concerning the development and healing of beta burns has been obtained from observations of the Marshall Islanders who were exposed to fallout in March 1954. Within about

5 hours of the burst, radioactive material commenced to fall on some of the islands. Although the fallout was observed as a white powder, consisting largely of particles of lime (calcium oxide) resulting from the decomposition of coral (calcium carbonate) by heat, the island inhabitants did not realize its significance. Because the weather was hot and damp, the Marshallese remained outdoors; their bodies were moist and they wore relatively little clothing. As a result, appreciable amounts of fission products fell upon and remained in contact with the hair and skin for a considerable time. Further, since the islanders, as a rule, did not wear shoes, their bare feet were continually subjected to contamination from fission products on the ground.

11.96 During the first 24 to 48 hours, a number of individuals in the more highly contaminated groups experienced itching and a burning sensation of the skin These symptoms were less marked among those who were less contaminated with fission products. Within a day or two all skin symptoms subsided and disappeared, but after the lapse of about 2 to 3 weeks, epilation and skin lesions were apparent on the areas of the body which had been contaminated by fallout particles. There was apparently no erythema, either in the early stages (primary) or later (secondary), as might have been expected, but this may have been obscured by the natural coloration of the skin.

11.97 The first evidence of skin damage was increased pigmentation, in the form of dark colored patches and raised areas (macules,

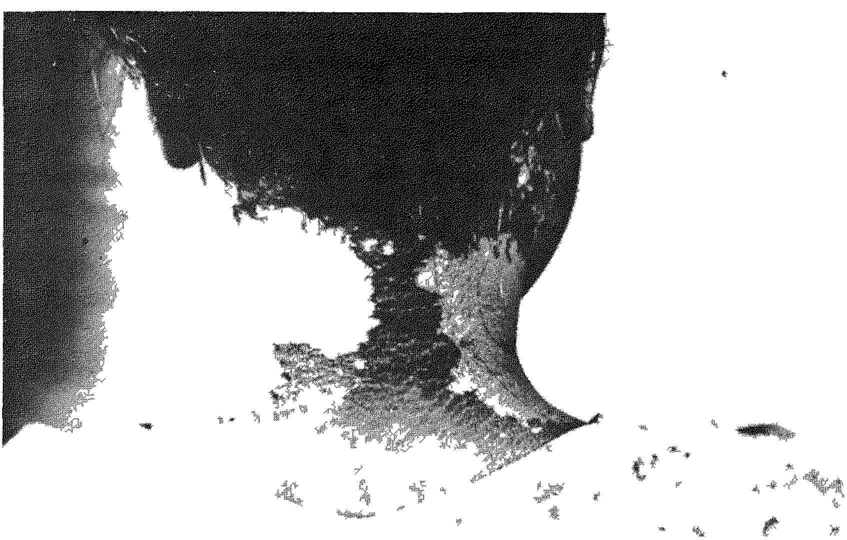

Figure 11.97a. Beta burn on neck 1 month after exposure

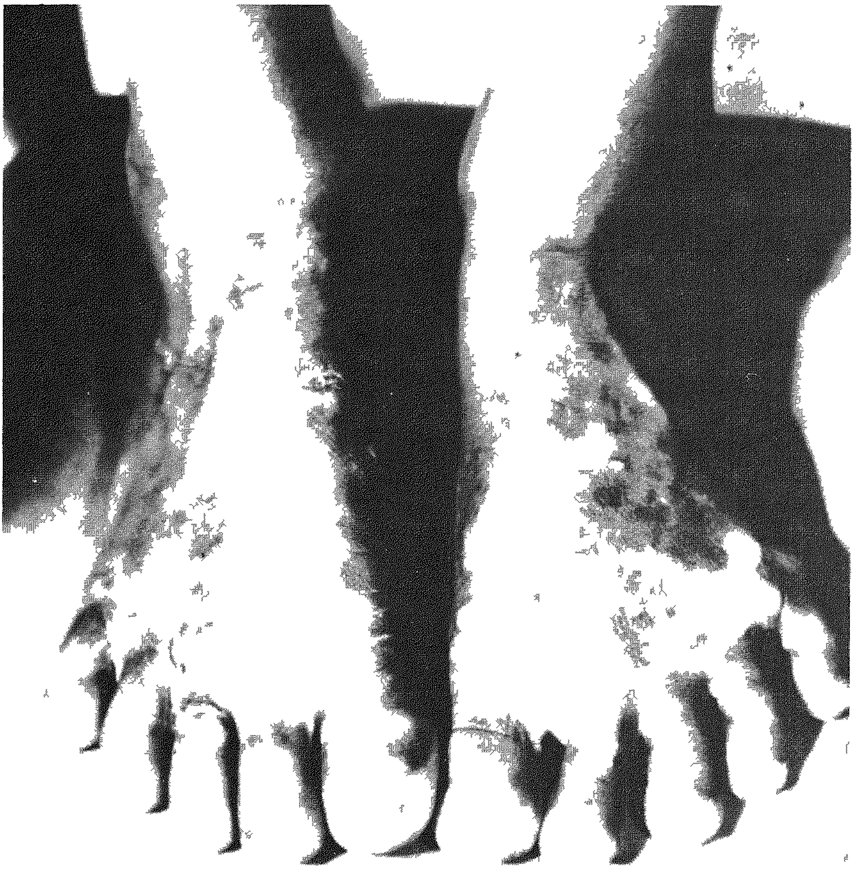

Figure 11.97b Beta burn on feet 1 month after exposure.

papules, and raised plaques). These lesions developed on the exposed parts of the body not protected by clothing, and occurred usually in the following order: scalp (with epilation), neck, shoulders, depressions in the forearm, feet, limbs, and trunk. Epilation and lesions of the scalp, neck, and foot were most frequently observed (Figs. 11.97a and b).

11.98 In addition, a bluish-brown pigmentation of the fingernails was very common among the Marshallese and also among American Negroes. The phenomenon appears to be a radiation response peculiar to the dark-skinned races. since it was not apparent in any of the white Americans who were exposed at the same time. The nail pigmentation occurred in a number of individuals who did not have skin lesions. It is probable that this was caused by gamma rays,

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rather than by beta particles, as the same effect has been observed in colored patients undergoing X-ray treatment in clinical practice.

11.99 Most of the lesions were superficial without blistering. Microscopic examination at 3 to 6 weeks showed that the damage was most marked in the outer layers of the skin (epidermis), whereas damage to the deeper tissue was much less severe. This is consistent with the short range of beta particles in animal tissue. After formation of dry scab, the lesions healed rapidly leaving a central depig-

Figure 11.100a. Beta burn on neck 1 year after exposure (see Fig. 11.97a).

Figure 11.100b. Beta burn on feet 6 months after exposure (see Fig. 11.97b).

mented area, surrounded by an irregular zone of increased pigmentation. Normal pigmentation gradually spread outward in the course of a few weeks.

11.100 Individuals who had been more highly contaminated developed deeper lesions, usually on the feet or neck, accompanied by mild burning, itching, and pain. These lesions were wet, weeping, and ulcerated, becoming covered by a hard, dry scab; however, the majority healed readily with the regular treatment generally employed for other skin lesions, not connected with radiation. Abnormal pigmentation effects persisted for some time, and in several cases about a year elapsed before the normal (darkish) skin coloration was restored (Figs. 11.100a and b).

11.101 Regrowth of hair, of the usual color (in contrast to the skin pigmentation) and texture, began about 9 weeks after exposure and was complete in 6 months. By the same time, nail discoloration had grown out in all but a few individuals.

Internal Sources of Radiation

11.102 Wherever fallout occurs there is a possibility that radioactive material will enter the body through the digestive tract (due to the consumption of food and water contaminated with fission products), through the lungs (by breathing air containing fallout particles), or through wounds or abrasions. The general biological effects of nuclear radiations from internally deposited sources are the same as those from external sources. However, it should be noted that even a very small quantity of radioactive material present in the body can produce considerable injury.

11.103 In the first place, radiation exposure of various organs and tissues from internal sources is continuous, subject only to depletion of the quantity of active material in the body as a result of physical (radioactive decay) and biological (elimination) processes. Further, the body tissues in which injury may occur are nearer the source of radiation and not shielded from it by intervening materials. This is of particular importance with alpha and beta particles which cannot reach sensitive regions, except the outer layers of the skin, if originating outside the body. But if the sources, e. g., plutonium (alpha-particle emitter) or fission products (beta-particle emitters) are internal, the particles can dissipate their entire energy within a small, possibly sensitive, volume of body tissue, thus causing considerable damage.

11.104 The situation just described is sometimes aggravated by the fact that certain chemical elements tend to concentrate in specific cells or tissues, some of which are highly sensitive to nuclear radiation. The fate of a given radioisotope which has entered the blood stream will depend upon its chemical nature. Radioisotopes of an element which is a normal constituent of the body will follow the same metabolic processes as the naturally occurring, inactive (stable) isotopes of the same element. This is the case, for example, with iodine which tends to concentrate in the thyroid gland.

11.105 An element not usually found in the body, except perhaps in minute traces, will behave like one with similar chemical properties that is normally present. Thus, among the fission products, strontium and barium, which are similar chemically to calcium, are largely

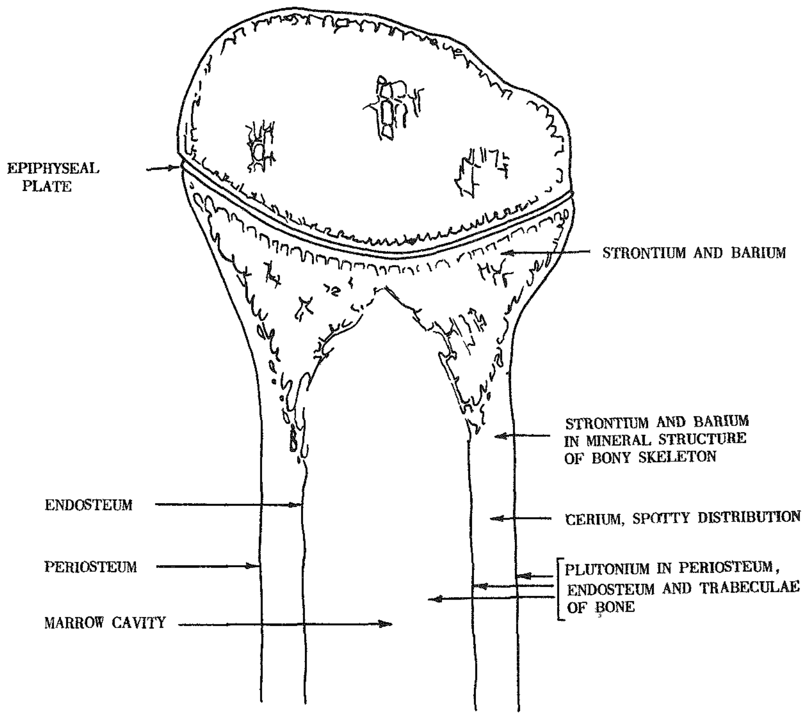

Figure 11.105. Deposition of elements in growing bone of rodents.

deposited in the calcifying tissue of bone. The radioisotopes of the rare earth elements, e. g., cerium, which constitute a considerable proportion of the fission products, and plutonium, which may be present to some extent in the fallout, are also "bone-seekers." Since they are not chemical analogues of calcium, however, they are deposited to a lesser extent and in other parts of the bone than strontium and barium (Fig. 11.105). All bone-seekers, are, nevertheless, potentially very hazardous because they can injure the sensitive bone marrow where many blood cells are produced. The damage to the blood-forming tissue thus results in a reduction in the number of blood cells and so adversely affects the entire body.

11.106 In order to constitute an internal radiation source, the active materials must gain access to the circulating blood, from which they can be deposited in the bones, liver, etc. While the radioactive substances are in the lungs, stomach, and intestines, they are, for all practical purposes, an external, rather than internal, source of radiation. The extent to which fallout contamination can get into the blood stream will depend upon two main factors: the size of the particles

and their solubility in the body fluids. Whether the material is subsequently deposited in some particular tissue will be determined by the chemical properties of the elements present, as indicated above. Elements which do not tend to concentrate in a particular part of the body are eliminated fairly rapidly by natural processes.

11.107 If other things, e. g., particle size and solubility, are equal, a greater proportion of the material entering the body by breathing will find its way into the blood than of that entering through the digestive system. This may be accounted for by the different mechanisms whereby materials pass through the lungs and the intestinal tract. The amount of radioactive material absorbed from fallout by inhalation, however, appears to be relatively small.

11.108 The reason is that the nose can filter out almost all particles over 10 microns (0.001 centimeter) in diameter, and about 95 percent of those exceeding 5 microns (0.0005 centimeter). Most of the particles descending in the fallout during the critical period of highest activity, e. g., within 24 hours of the explosion, will be considerably more than 10 microns in diameter (§ 9.125, *et seq.*). Consequently, only a small proportion of the fallout particles present in the air will succeed in reaching the lungs. Further, the optimum size for passage from the alveolar (air) space of the lungs to the blood stream is less than 5 microns. The probability of entry into the circulating blood of fission products and other bomb residues present in the fallout, as a result of inhalation, is thus low.

11.109 The extent of absorption of fission products and other radioactive materials through the intestine is largely dependent upon the solubility of the particles. In the fallout, the fission products, as well as uranium and plutonium, are chiefly present as oxides, many of which do not dissolve to any great extent in body fluids. The oxides of strontium and barium, however, are soluble, so that these elements can readily enter the blood stream and find their way into bones. The element iodine is also chiefly present in a soluble form; it soon enters the blood and is concentrated in the thyroid gland.

11.110 In addition to the tendency of a particular element to be taken up by a radiosensitive organ, the main consideration in determining the hazard from a given radioactive isotope inside the body is the total biological dose delivered while it is in the body (or critical organ). The most important factors in determining this dose are the mass and half-life (§ 1.49) of the radioisotope, the nature and energy of the radiations emitted, and the length of time it stays in the body. This time is dependent upon two factors; one is the ordinary radio-

active half-life and the other is called the "biological half-life." The latter is defined as the time taken for the amount of a particular element in the body to decrease to half of its initial value due to elimination by natural (biological) processes. Combination of the radioactive and biological half-lives gives rise to the "effective half-life," which is the time required for the amount of a specified radioactive isotope in the body to fall to half of its original value as a result of both radioactive decay and natural elimination. In most cases of interest, the effective half-life in the body as a whole is essentially the same as that in the principal tissue (or organ) in which the element tends to concentrate.

11.111 The isotopes representing the greatest potential internal hazard are those with short radioactive half-lives and comparatively long biological half-lives. A certain mass of an isotope of short radioactive half-life will emit particles at a greater rate than the same mass of another isotope, possibly of the same element, having a longer half-life. Further, the long biological half-life means that the active material will not be readily eliminated from the body by natural processes. For example, the element icdine has a biological half-life of about 180 days, because it is quickly taken up by the thyroid gland from which it is eliminated slowly. The radioisotope iodine-131, a fairly common fission product, has a radioactive half-life of only 8 days. Consequently, if a sufficient quantity of this isotope enters the blood stream it is capable of causing serious damage to the thyroid gland. It should be mentioned that, apart from immediate injury, any radioactive material that enters the body, even if it has a short effective half-life, may contribute to damage which does not become apparent for some time.

11.112 In addition to radioiodine, the most important potentially hazardous fission products, assuming sufficient amounts get into the body, fall into two groups. The first, and more significant, contains strontium-89, strontium-90, and barium-140, whereas the second consists of a group of rare earth and related elements, particularly cerium-144 and the chemically similar yttrium-91. As seen earlier, these elements are readily deposited and held in various parts of the bone where the emitted beta and gamma radiations can injure blood-forming tissues and may also cause tumor formation.

11.113 Another potentially hazardous element, which may be present to some extent in the fallout, is plutonium, in the form of the alpha-particle emitting isotope plutonium-239, that has escaped

fission. Plutonium-239 has a long radioactive half-life (24,000 years) as well as a long biological half-life (over 100 years). Consequently, once it is deposited in the body, mainly on certain surfaces of the bone (Fig. 11.105), the amount of plutonium present, and its activity, decrease at a very slow rate. In spite of their short range in the body, the continued action of alpha particles over a period of years can cause significant injury. In sufficient amounts, radium, which is very similar to plutonium in these respects, is known to cause necrosis and tumors of the bone, and anemia resulting in death.

11.114 In addition to concentrating in skeletal tissue, strontium, barium, and plutonium are found to accumulate to some extent in both liver and spleen. The rare earths also deposit in the liver and to a lesser extent in the spleen. However, many radioisotopes are readily eliminated from the liver. It is of interest to note that despite the large amounts of radioactive material that may pass through the kidneys, in the process of elimination, these organs ordinarily are not greatly affected. By contrast, uranium causes damage to the kidneys, but as a chemical poison rather than because of its radioactivity.

Experience With Fallout as an Internal Hazard

11.115 The fallout accompanying the nuclear air bursts over Japan was so insignificant that no information was available concerning the potentialities of fission products and other bomb residues as internal sources of radiation. Following the incident in the Marshall Islands in March 1954, however, data of considerable interest were obtained. Because they were not aware of the significance of the fallout, many of the inhabitants ate contaminated food and drank contaminated water from open containers for periods up to 2 days or so.

11.116 Internal deposition of fission products resulted mainly from ingestion rather than inhalation for, in addition to the reasons given above, the radioactive particles in the air settled out fairly rapidly, but contaminated food, water, and utensils were used all the time. The belief that ingestion was the chief source of internal contamination was supported by the observations on chickens and pigs made soon after the explosion. The gastro-intestinal tract, its contents, and the liver were found to be more radioactive than lung tissue.

11.117 From radiochemical analysis of the urine of the Marshallese subjected to the fallout, it was possible to estimate the body burden, i. e., the amounts deposited in the tissues, of various isotopes. It was found that iodine–131 made the major contribution to the activity at

the beginning, but it soon disappeared because of its relatively short radioactive half-life (8 days). Somewhat the same was true for barium–140 (12.8 days half-life), but the activity of the strontium isotopes was more persistent. Not only do they have longer radioactive half-lives, but the biological half-life of the element is also relatively long.

11.118 No elements other than iodine, strontium, barium, and the rare earth group were found to be retained in appreciable amounts in the body. Essentially all other fission product and bomb residue activity is rapidly eliminated, because of either the short effective half-lives of the radioisotopes, the sparing solubility of the oxides, or the relatively large size of the fallout particles.

11.119 The body burden of radioactive material among the more highly contaminated inhabitants of the Marshall Islands was never very large and it decreased fairly rapidly in the course of 2 or 3 months. The activity of the strontium isotopes fell off somewhat more slowly than that of the other radioisotopes, because of the longer radioactive (and biological) half-life and greater retention in the bone. Nevertheless, even strontium could not be regarded as a dangerous source of internal radiation in the cases studied. At 6 months after the explosion, the urine of most individuals contained only barely detectable quantities of radioactive material, indicating that the body burden was then extremely small.

11.120 In spite of the fact that the Marshallese people lived under conditions where maximum probability of contamination of food and water supplies existed, and that they took no steps to protect themselves in any way, the degree of internal hazard due to the fallout was small. There seems to be little doubt, therefore, that, at least as far as short term effects are concerned, the radiation injury by fallout due to internal sources is quite minor in comparison with that due to the external radiation. If reasonable precautions are taken, as will be described in Chapter XII, the short term, internal hazard can probably be greatly reduced.

Long-Term Internal Hazard

11.121 Apart from the possible long-term effects of radioactive material that has been inhaled or ingested and subsequently eliminated, about which little is yet known, there has been some speculation concerning the relatively long lived strontium-90, to which reference was made in Chapter X. Perhaps because one of the predecessors

of strontium-90, namely krypton-90, is a gas, the initial fission products, especially those deposited in the region of the more-or-less immediate fallout, are somewhat depleted in this isotope of strontium. In any event, to judge from the experience with the inhabitants of the Marshall Islands, the probability that strontium will be taken up and held firmly in the body as a result of inhalation or ingestion of local fallout particles is not great. The possibility that strontium-90 may be absorbed over the course of time in certain foods is, however, a different matter.

11.122 As discussed in Chapter X, the strontium-90 and other fission products that have entered the stratosphere as very small particles, will eventually settle to the ground. The strontium may then find its way, mainly through milk and milk products, into the human body. Because it is eliminated slowly by natural processes, the strontium-90, with a radioactive half-life of about 28 years, will accumulate in the skeletal structure of the body. If sufficient quantities are present, the long-term injuries may be similar to those caused by excessive amounts of radium and plutonium, described above (§ 11.113).

GENETIC EFFECTS OF RADIATION

Spontaneous and Induced Mutations

11.123 The genetic effects of radiation are effects of a long-term character which produce no visible injury in the exposed individual but may have notable consequences in future generations. These effects differ from most other changes produced by nuclear radiation in that they appear to be cumulative and, to a great extent, independent of the dose rate. In other words, the extent of the genetic effects depends upon the total radiation dose received and not on whether the exposure is of short duration or spread over many years. Thus, as far as genetic changes are concerned, it is largely immaterial whether the radiation dose is chronic or acute.

11.124 The mechanism of heredity, which is basically similar in all sexually reproducing plants and animals, including man, is somewhat as follows. The nuclei of all dividing cells contain a definite number of thread-like entities called "chromosomes" that are visible under the microscope. These chromosomes are believed to be differentiated along their length into thousands of distinctive units, referred to as "genes." The chromosomes (and genes) exist in every cell of the body, but from the point of view of genetics (or heredity), it is only those in the germ cells, which exist in the reproductive organs, that are important.

11.125 Human body cells normally contain 48 chromosomes, made up of two similar (but not identical) sets of 24 chromosomes each.[5] One of these sets was inherited from the mother, for the egg cell (produced in the ovaries) carries a set of 24 chromosomes, whereas the other set came from the father, for the sperm cell (produced in the testes) carries a set of 24 similar (but not identical) chromosomes. As the individual develops, following upon the fusion of the original egg and sperm cells, the chromosomes and genes are, in general, duplicated without change.

11.126 In rare instances, however, a deviation from normal behavior occurs and instead of a chromosome duplicating itself in every respect, there is a change in one or more of the genes. This change, called a "mutation," is essentially permanent, for the mutant gene is reproduced in its altered form. If this mutation occurs in a body cell, there may be some effect on the individual, but the change is not passed on. But if the mutation occurs in a germ cell of either parent, a new characteristic will appear in a later generation. The mutations which occur naturally, without any definitely assignable cause or human intervention, are called "spontaneous mutations."

11.127 The matter of immediate interest is that the frequency with which mutations occur can be increased in various ways, one being by exposure of the sex glands (or "gonads"), i. e., testes or ovaries, to radiation. This effect of radiation has been observed with various insects and mammals, and it undoubtedly occurs also in human beings. The gene mutations induced by radiation do not differ qualitatively from those occurring spontaneously. In practice, it is impossible to determine in any particular instance whether the change has occurred naturally or whether it was due to radiation. It is only the frequency with which the mutations occur that is increased by radiation.

11.128 All genes have the property of being either "dominant" or "recessive." If a gene is dominant, then the appropriate characteristic affected by that gene will appear in the offspring even if it is produced by the gonads of only one of the parents. On the other hand, a particular recessive gene must occur in the gonads of both parents if the characteristic is to be apparent in the next generation. A recessive gene may consequently be latent for a number of generations, until the occasion arises for the union of sperm and egg cells both of which contain this particular gene.

11.129 As a general rule, new mutations, whether spontaneous or induced by radiation, are recessive. Nevertheless, it appears that a mutant gene is seldom completely recessive, and some effect is ob-

[5] Recent evidence indicates that these numbers may be 46 and 23, respectively.

servable in the next generation even if the particular gene is inherited from only one parent. Further, in the great majority of cases, mutations have deleterious effects of some kind. A very few of the changes accompanying mutations are undoubtedly beneficial, but their consequences become apparent only in the slow process of biological evolution.

11.130 The harmful effects of a deleterious mutation may be quite minor, such as increased susceptibility to disease or a decrease in life expectancy by a few months, or they may be more serious, such as death in the embryonic stage or the inability to produce children at all. Thus, individuals bearing harmful genes are handicapped relative to the rest of the population, particularly in the respects that they tend to have fewer children or to die earlier. It is apparent, therefore, that such genes will eventually be eliminated from the population. A gene that does great harm will be eliminated rapidly, since few (if any) individuals carrying such genes will survive to the age of reproduction. On the other hand, a slightly deleterious mutant gene may persist much longer, and thereby do harm, although of a less severe character, to a larger number of individuals.

Mutations and Radiation Dose

11.131 Experiments with various types of animals have shown that the increased frequency of the occurrence of gene mutations, as a result of exposure to radiation, is approximately proportional to the total amount of radiation absorbed by the gonads of the parents from the beginning of their development to the time of conception of the progeny. There is apparently no amount of radiation, however small, that does not cause some increase in the normal mutation frequency. The dose rate of the radiation exposure or its duration have little influence; it is the total accumulated dose to the gonads that is the important quantity. It should be pointed out, however, that a large dose of radiation does not mean that the resulting mutations will be more harmful than for a smaller dose. With a large dose the mutations will be of the same general type as for a small dose, or as those which occur spontaneously, but there will be more of them in proportion to the dose.

11.132 In reviewing the possible genetic effects resulting from the use of nuclear weapons, there are two aspects to be considered. First, the consequences of exposure to the initial and residual radiations soon after the explosion, and second, the results of the slow accumulation of strontium-90 (and perhaps other fission products) in the body.

Of these two, the former is undoubtedly more important. It has been estimated that the amount of radiation, in addition to that received from natural background sources (§ 9.41), required to double the rate at which spontaneous mutations are already occurring, is a dose to the gonads of probably between 30 and 80 roentgens, prior to conception, for each member of the population. A proportionately larger dose to a smaller fraction of the populace would have a somewhat similar effect on the frequency of mutations and their ultimate consequences.

11.133 The genetic effects of strontium-90, on the other hand, may be expected to be very small. This isotope tends to accumulate in the skeleton, and since it emits only beta particles, but no gamma rays, the radiation dose to the gonads from strontium-90 in bone will be of minor significance. The same would be generally true for other fission products that might be concentrated in the skeleton or other parts of the body.

PATHOLOGY OF RADIATION INJURY[6]

Cellular Sensitivity

11.134 The discussion presented above has been mostly concerned with over-all symptoms and effects of radiation injury; even the changes in the blood are, to a great extent, indirectly due to the action of nuclear radiation on the bone marrow and lymphatic tissue. It is of interest, therefore, to consider briefly the pathological changes produced by radiation in some individual organs and tissues.

11.135 The damage caused by radiation undoubtedly originates in the individual cells. As mentioned in § 11.45, a number of observable changes in the cells and their contents results from exposure to nuclear radiation. Different types of cells show remarkable variations in their response. In general, rapidly multiplying or actively reproducing cells are more radiosensitive than are those in a more quiescent state. One of the most striking effects of irradiation is the sharp decrease or even complete cessation of cell division (mitosis) in organs which are normally in a state of continuous regeneration.

11.136 Of the more common tissues, the radiosensitivity decreases in the following order: lymphoid tissue and bone marrow; epithelial tissue (tests and ovaries, salivary glands, skin, and mucuous mem-

[6] The remaining sections of this chapter may be omitted without loss of continuity.

brane); endothelial cells of blood vessels and peritoneum; connective tissue cells; bone cells, muscle cells, and differentiated (or specialized) nerve cells. However, some brain and nerve cells, especially those of embryos, are fairly sensitive to radiation. The behavior of certain of these tissues under the influence of radiation is outlined below.

Lymphoid Tissue

11.137 The lymphoid tissue is the tissue characteristic of lymph glands, tonsils, adenoids, spleen, and certain areas of the intestinal lining. The so-called lymph glands, found in various parts of the body, are a network of connective tissue in the meshes of which are the lymphoid cells. These cells, when mature, are carried off by the lymph fluid, flowing through the glands, and become the lymphocyte constituents of the white blood cells (§ 11.77). As indicated in the preceding paragraph, the lymphoid tissue is one of the most radiosensitive of all tissues.

11.138 Lymphoid cells are injured or killed when the tissue is exposed to radiation. Microscopic examination shows degenerative changes characteristic of cell death. The degeneration of the lymphoid tissue, including the formation of cells of abnormal types, was an outstanding phenomenon among the victims of the nuclear bombs in Japan. Damage to the lymphoid cells accounts for the decrease in the number of lymphocytes in the circulating blood; the radiation not only damages the lymphocyte-bearing tissue but it may also kill or injure the lymphocytes already in the blood. It appears that if there is no appreciable drop in the lymphocyte count within 72 hours of exposure to radiation, the dose has been too small to cause any significant sickness.

11.139 Lymphoid tissue injured by radiation tends to become edematous, that is, to swell due to the accumulation of serous fluid. Wasting of the lymph glands, as well as of the tonsils and lymphoid patches of the intestines, was common among the radiation casualties in Japan.

Bone Marrow

11.140 Since most of the constituent cells of the blood, other than the lymphocytes, are produced in the bone marrow, the fact that this tissue is very radiosensitive is of great importance. Under normal circumstances, the mature blood cells leave the marrow and make

their way into the blood stream. Here they remain for various periods before being destroyed by natural processes. In general, the shorter the life of a particular type of blood cell, the more quickly will it reveal evidence of radiation injury by a decrease in the number of such cells. The red blood cells, which have the longest lives, are the last to show a reduction in number after exposure to radiation (§ 11.80).

11.141 Bone marrow exhibits striking changes soon after irradiation. The tissue forming the blood cells ceases to function and in some severe cases in Japan it was observed that tissue which normally produces granulocytes was forming plasma-like cells. Extreme atrophy of the bone marrow was characteristic of many of those dying from radiation injury up to 3 or 4 months after exposure, although there was some evidence of attempts of the body at repair and regeneration. In some instances a gelatinous deposit had replaced the normal bone marrow.

Reproductive Organs

11.142 Almost every post mortem examination of males dying from radiation exposure revealed profound changes in the testes. Even as early as the fourteenth day after exposure, when gross changes were not apparent, microscopic observation showed alterations in the layers of epithelium from which the spermatozoa develop. Many of the cells were degenerated, and evidence of healthy cell division was lacking.

11.143 Although the ovaries were also highly radiosensitive, the obvious changes, as observed among females in Japan, appeared to be less striking than in the testes in males. Except for hemorrhages, as part of the general tendency to bleed, there were no especially significant changes of either a gross or a microscopic character. In many cases among survivors, the ova were not developing normally after exposure, and this induced alterations in the menstrual cycle. Cessation of menstruation occurred, but it was transient. There was an increased incidence of miscarriages and premature births, and a greater death rate among expectant mothers. In general, these manifestations varied in severity according to the proximity of the individual to the explosion center.

11.144 In connection with changes in the reproductive organs, it may be noted that the dose required to produce sterility in human beings is believed to be from 450 to 600 roentgens, which would be lethal in most cases if received over the whole body. Temporary

sterility can occur with smaller doses, however, as happened among Japanese men and women. The great majority of these individuals have since returned to normal, although it cannot be stated with certainty that all have recovered, because many were undoubtedly sterile from other causes, such as disease and malnutrition. Many who were exposed to appreciable doses of radiation have since produced apparently normal children, as noted earlier.

Loss of Hair

11.145 Epilation (loss of hair), mainly of the scalp, was common among those Japanese who survived for more than 2 weeks after the explosion. The time of onset of epilation reached a sharp peak, for both males and females, between the thirteenth and fourteenth days. The hair suddenly began to fall out in bunches upon combing or plucking, and much fell out spontaneously: this continued for 1 or 2 weeks and then ceased.

11.146 In most instances the distribution of epilation was that of ordinary baldness, involving first the front, and then the top and back of the head. The hair of the eyebrows and particularly the eyelashes and beard came out much less easily. In a small group of Japanese, which may or may not have been typical, 69 percent had lost hair from the scalp, 12 percent from the armpits, 10 percent from pubic areas, 6 percent from the eyebrows, and 3 percent from the beard. In severe cases, hair began to return within a few months and in no instance was the epilation permanent.

Gastro-Intestinal Tract

11.147 The mucous linings of the gastro-intestinal tract were among the first tissues to show gross changes in the irradiated Japanese. Even before hemorrhage and associated phenomena were noticed, there was swelling, discoloration, and thickening of the mucous membranes of the caecum (blind gut) and large intestine. Patches of lymphoid tissue were especially involved. In many patients there was first swelling, then ulceration of the most superficial layers of the mucous membranes of the intestinal tract, proceeding to deeper ulceration, and a membrane-like covering of the ulcer, suggesting, but not entirely simulating, that seen in bacillary dysentery.

11.148 In the third and fourth weeks, inflammation of the intestines, and occasionally of the stomach, was a common post-mortem

observation. In the early stages the small intestine was affected but later, among those who survived, the whole of the large intestine, from the lower end of the small intestine to the rectum, was involved. Thickening of the intestinal wall and a tendency to produce false membranes were common features, as in acute bacillary dysentery. The effects apparently depended upon the devitalization of tissues as a primary result of irradiation, lowered local resistance, and lowered efficiency of the defense mechanisms ordinarily supplied by the components of the circulating blood. Under the microscope, notable changes were the swelling of cells and the absence of infiltration of the white blood cells.

Hemorrhage and Infection

11.149 Certain parts of the urinary tract, the muscles, and all the soft tissues of the body may show subsurface hemorrhage varying in size from a pin-point to several inches across. These changes are significant, for they present clinical evidence of the nature and severity of radiation injury. If the hemorrhages occur in important centers of the body, e. g., the heart, lungs, or brain, the consequences may be disastrous. The damage depends upon the location of the large hemorrhagic lesions in relation to the tissues of the particular vital organ involved. Some hemorrhages present external signs, or may be observed upon examination, such as those into the linings of the mouth, nose, and throat, behind the retina of the eye, or into the urinary tract. Large hemorrhagic lesions may occur in the drainage tracts of the kidney, in the small tubes leading from the kidney to the bladder, and in the urinary bladder.

11.150 Hemorrhages breaking through a surface layer of epithelium, laden with bacteria, may give rise to other effects. The tissues may become devitalized and so lacking in resistance to infection that they make an ideal place for the multiplication of bacteria that are either weakly invasive or rarely dangerous under ordinary circumstances. This bacterial invasion may lead to serious local tissue destruction and perhaps systemic infection. Normally harmless bacteria, generally found within the digestive tract and on the skin, may actually gain access to the blood stream and cause blood poisoning and fatal infection. Boils and abscesses may form in any part of the body through a similar cause, but they are characterized by being more localized.

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11.151 When this form of tissue change occurs in the throat, the medical findings may resemble a condition found after certain chemical intoxications that injure the bone marrow and the reticulo-endothelial system. In other instances, they may be similar to that observed in some blood diseases associated with an absence of granulocytes in the circulating blood (agranulocytosis). In radiation sickness, ulcers may extend to the tongue, the gums, the inner lining of the mouth, the lips, and even the outer part of the skin of the face. These ulcerations may occur independently of any associated local hemorrhagic change. Similar effects have been observed throughout the entire gastro-intestinal tract. Within the lungs, a form of pneumonia may develop which differs from most pneumonias in the almost complete absence of infiltrating white blood cells.

12.15 In general, there are three main aspects in which blast-resistant design differs from the design procedures for static loads. First, mass is important, since, as structural displacement takes place, the various masses undergo large accelerations. Other things being equal, a heavy structure will usually withstand the action of blast better than one that is less massive. Second, many structural materials, including steel, concrete, and even wood, exhibit increased strength when subjected to rapid rates of strain, such as would occur when exposed to a blast wave. For high rates of loading the yield point may be increased 50 percent or more over the value at low rates of loading. Third, if ductile materials are used in blast-resistant design, it is possible and may be desirable for economic reasons to permit strains beyond the elastic limit.

12.16 Some degree of permanent deformation may be acceptable before a structure is rendered useless for its main purpose, and this can be taken into consideration in its design. The steel-mill type of building is a good example of a structure in which large permanent deformation may be accepted. On the other hand, office buildings, apartment houses, etc., containing elevator shafts, partitions, doors, windows and concealed utilities, may have their usefulness impaired by much smaller deformations.

12.17 In designing a particular type of structure to resist blast, it is necessary first to postulate the blast wave characteristics, i. e., the peak overpressure and dynamic pressure, and their variation with time. These factors depend upon the energy yield of the explosion, the expected distance of the structure from the point of burst, and the height of burst. Since none of these variables can possibly be known in advance, the postulates concerning the blast load which the structure is required to withstand inevitably involve considerable uncertainty. The choice of the blast load for design purposes must be based on a balance between the cost and the over-all importance of the particular structure.

12.18 After the loading has been prescribed, a dynamic analysis of the proposed structure must be undertaken to determine the stiffness and ultimate strength necessary to prevent collapse or to limit the plastic deformation to some specified amount. This limit will be determined by the functional requirements of the activities or operations for which the structure is to be used. The critical deformation may be restricted to that which will prevent the structure from collapsing, so that personnel can be protected and the contents of the building salvaged; or it may be required that the building shall still be capable of use for conventional loads after the blast. The next step in the

design is then to prepare specifications of the structural members and connections to supply the required strength and stiffness.

12.19 The detailed methods and procedures of dynamic design are probably necessary in order to predict accurately the behavior of a structure exposed to loading from a blast wave. However, this requires familiarity with methods not customarily used in conventional engineering design.

Structural Materials

12.20 In choosing structural materials it should be borne in mind that the energy absorbed by a structure undergoing plastic deformation can make an important contribution to resistance to dynamic loading. Brittle materials, e. g., glass, cast iron, and unreinforced masonry, cannot tolerate strains beyond the elastic limit without suffering failure by rupture. Upon failure, these materials can produce dangerous missiles and so should be avoided for this reason also (see § 12.35). On the other hand, ductile materials, e. g., structural steel, reinforced concrete, and reinforced masonry, can undergo considerable plastic deformation without collapse and, in many cases, without appreciable loss of strength.

12.21 Reinforced concrete offers many advantages as a structural material, since it has characteristics desirable in blast-resistant construction. The large mass and sluggish response of the relatively heavy members, and the continuity which is possible, contribute to the ability to withstand lateral forces. Concrete can be used for shear walls which provide resistance to motion and add little to the cost of the building.[2] The bulkiness of the members may be somewhat objectionable, although thick concrete walls can help in attenuating nuclear radiation.

Types of Blast-Resistant Multistory Structures

12.22 The type and arrangement of a structure designed to have appreciable resistance to blast will depend, to some extent, upon the intended use of the structure. In general, the ability to withstand the lateral forces due to blast will increase with the strength, rigidity, ductility, and mass of the members enclosing and supporting the

[2] Shear walls are walls (or partitions) designed for horizontal loads applied in the plane of the wall, as distinct from loads perpendicular to the wall. Shear walls may, of course, be designed to take such lateral loads as well

structure. There are, however, certain structural forms which are inherently more suited to resist blast loading.

12.23 If the presence of solid or almost solid exterior walls and cross walls can be tolerated in the functional layout of the building, a satisfactory and economical design for a multistory structure appears to be a reinforced-concrete, shear-wall building. Shear-wall structures derive their principal strength from structural walls capable of resisting large lateral loads. Such walls are usually so stiff compared to beams and columns, which may be used in conjunction with shear walls, that essentially all the translational load is carried by these walls.

12.24 Where interior walls are required as fire barriers, stairwell enclosures, or partitions, these may be designed, with advantage, as shear walls. The same walls can then be used to carry vertical loads, thus replacing the framing ordinarily employed for this purpose. It is desirable, however, in the construction of bearing walls, supporting floor and roof systems, to avoid the use of unreinforced brick, stone, or block, since they are vulnerable to relatively low pressures acting transversely to the walls.

12.25 When the operations to be performed in the building are such as to rule out solid (or nearly solid) exterior walls, then partially solid shear walls at the ends of the building, in addition to fire walls and fixed partitions of shear-wall design, are desirable. This will permit the use of light columns designed to carry the vertical loads for the rest of the framing. Even if shear walls are limited to stairwells, elevator shafts, and to walls around the plumbing and duct passages, an important degree of blast resistance can be achieved at minimum cost.

12.26 The presence of window openings and light curtain walls may have some advantages. Windows and light partitions will fail rapidly, when exposed to blast, without offering substantial resistance. As a result there will be a decrease in the lateral impulsive load, due to the reduction in the effective resisting area, before appreciable deformation occurs. While these openings might be helpful in minimizing damage to the frame and decreasing the danger of overturning, they may be expected to increase both the hazard to personnel in the building and the destruction of its contents.

12.27 In the construction of a reinforced-concrete building it is essential that there should be good continuity at all joints subject to appreciable bending or shearing stresses in order to insure monolithic behavior. All intersecting walls and floors should be securely doweled together with reinforcement, and construction joints between previ-

ously poured and fresh concrete should be prepared to provide maximum bonding between the old and the new.

12.28 A reinforced-concrete structure, with shear walls and partitions having good continuity, will act as a single cell. The walls of the structure will then transmit floor and roof reactions to the foundations. Heavy beams or supporting columns can thus be eliminated and good resistance to blast forces retained.

12.29 For steel-frame structures with diagonal bracing there is a possibility of complete failure by local rupture of the bracing material. Sufficient load-carrying capacity must be provided in the bracing to prevent this from occurring. In order to insure full utilization of the members of the frame, the strength of the end connections of a diagonal brace should always be greater than that of the member itself.

12.30 In tier buildings with steel skeleton frames, the strength of the end connections should be sufficient to develop the ultimate strength of the members of the frame. If the floor slabs are keyed to the structural steel frame by means of bond or shear developers, so as to provide composite behavior, both the steel and the concrete contribute strength to the framework. Wall panels should be attached to the building frames in such a manner that the connections will withstand rebound loads as well as the positive and negative loads due to the blast wave.

Reducing Blast Hazard in Existing Buildings

12.31 Aside from the question of the design of new construction considered above, there is the possibility of making changes in existing buildings so as to reduce the damage to their contents and injury to personnel resulting from blast action. This is a more difficult problem than that of incorporating appropriate measures in new design. The most serious danger to persons and equipment in a building is from total, or even partial, collapse. It is necessary, therefore, to analyze the structure in order to discover the weak points, and then to determine the best methods for strengthening them.

12.32 As a general rule, it will not be possible to strengthen the frame of a reinforced-concrete building, but increased resistance to collapse can be achieved by replacing interior walls, wherever possible, by shear walls. The addition of bracing can be effective in increasing the strength of a steel-frame building.

12.33 From an over-all point of view, an important consideration is the reduction in hazard to persons in a building strong enough not

to collapse even though it might be damaged to some extent. Well-attached, reinforced-concrete or reinforced-masonry walls, on a frame of either structural steel or reinforced concrete, will provide a high degree of protection to persons inside the building. This type of construction will also contribute a minimum number of missiles. A poorly attached wall of unreinforced masonry, on the other hand, would provide almost no protection inside the building and would supply missiles both inside and outside.

12.34 Existing frames of steel or reinforced concrete may be strengthened by filling the areas between the columns and beams with shear walls. The effectiveness of such walls will depend upon their strength and also upon the strength of the connections between shear walls and floors, since in order for such walls to be effective they must carry the lateral forces to the foundation. Inclusion of shear walls of this type in a frame structure creates a new unit of greatly increased strength.

12.35 In all structures, no matter how blast resistant they may be, it is important to minimize the danger from flying glass, displaced equipment, falling fixtures, and false ceilings. The great hazard to personnel due to glass should be considered in design, and glass areas should be provided only to the extent essential for the use of the building.

12.36 Consideration should be given to the hazard in existing structures from fixtures and heavier ornamental plaster or other interior treatment that might be detached by the blast or by the wracking action of the building. The best procedures would be to remove any such hazardous items if possible. If this is not fully practicable, such partial safeguards should be provided as may appear feasible. Overhanging cornices and finials on the outside of a building will be a danger to persons in the vicinity, and their removal should be considered. Although the flying missile hazard is not peculiar to nuclear weapons, it is, nevertheless, one which is greatly magnified by the high pressures and long duration of the blast wave.

12.37 Blast walls of the type employed to localize destruction from ordinary high-explosive bombs will perhaps be helpful, to some extent, in reducing injuries from flying missiles and in protecting essential equipment (Figs. 12.37a and b). Particular care should be taken to make such walls resistant to overturning. Both reinforced-concrete walls and earth-filled wooden walls (Fig. 12.37c) were used in Japan for protection against blast. The former were more effective, but the latter, even though badly damaged by the nuclear bomb blast, did prevent serious harm to equipment.

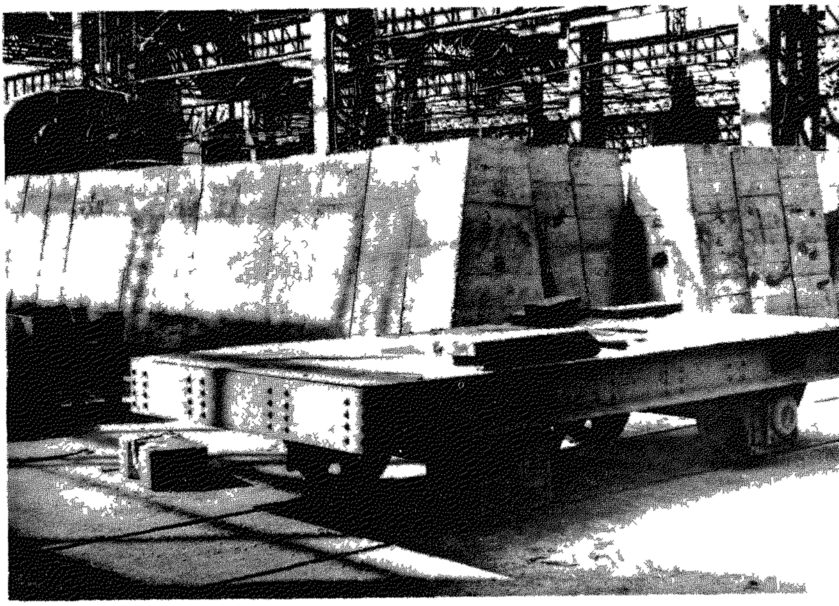

Figure 12.37a. Precast, reinforced-concrete blast walls (0.85 mile from ground zero at Nagasaki).

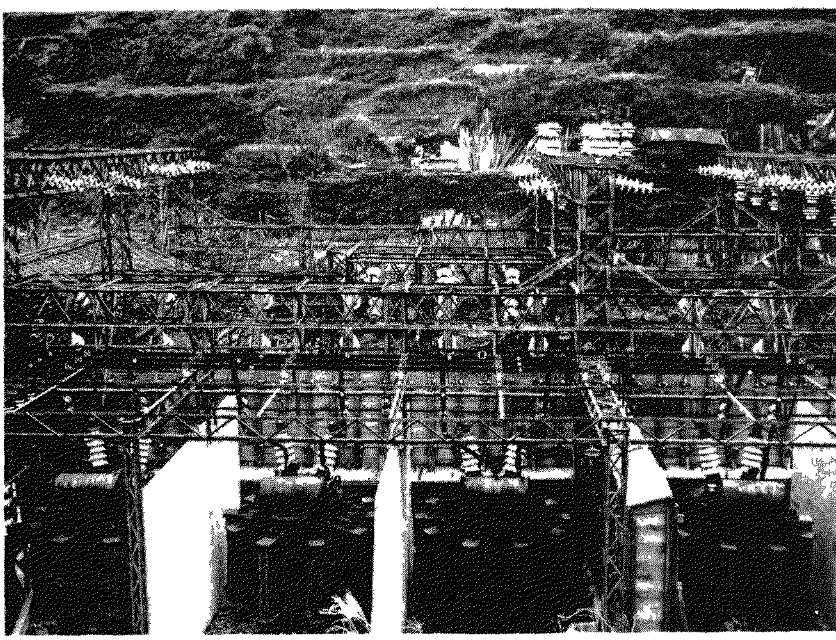

Figure 12.37b. Reinforced-concrete blast walls protecting transformers (1 mile from ground zero at Nagasaki).

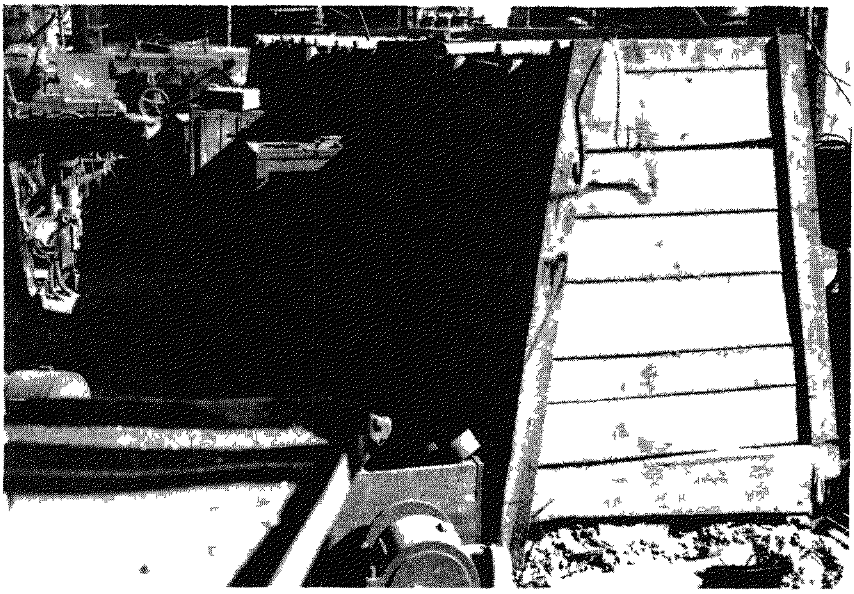

Figure 12.37c. Earth-filled, wooden blast walls protecting machinery (0.85 mile from ground zero at Nagasaki).

Protection by Trenches and Earth Revetments

12.38 Although they are not strictly structures, in the sense used above, attention should be called to the significant protection that can be afforded by trenches and earth revetments, especially to drag-sensitive targets. A shallow pit provides little shielding, but pits or trenches that are deeper than the target have been found to be very effective in reducing the magnitude of the drag forces impinging on any part of the target. In these circumstances, the lateral loading is greatly reduced and the damage caused is restricted mainly to that due to the crushing action of the blast wave.

12.39 The only types of shielding against drag forces which have been found to be satisfactory so far are those provided by fairly extensive earth mounds (or revetments) and deep trenches, since these are themselves relatively invulnerable to blast. Such protective trenches are not recommended for use in cities, however, because of the damage that would result from debris falling into them. Although sandbag mounds have proved satisfactory for protection against conventional high explosives and projectiles, they are inadequate against nuclear blast because they may become damaging missiles.

Figure 12.40a. Earth-moving equipment subjected to nuclear blast in open terrain (30 psi overpressure).

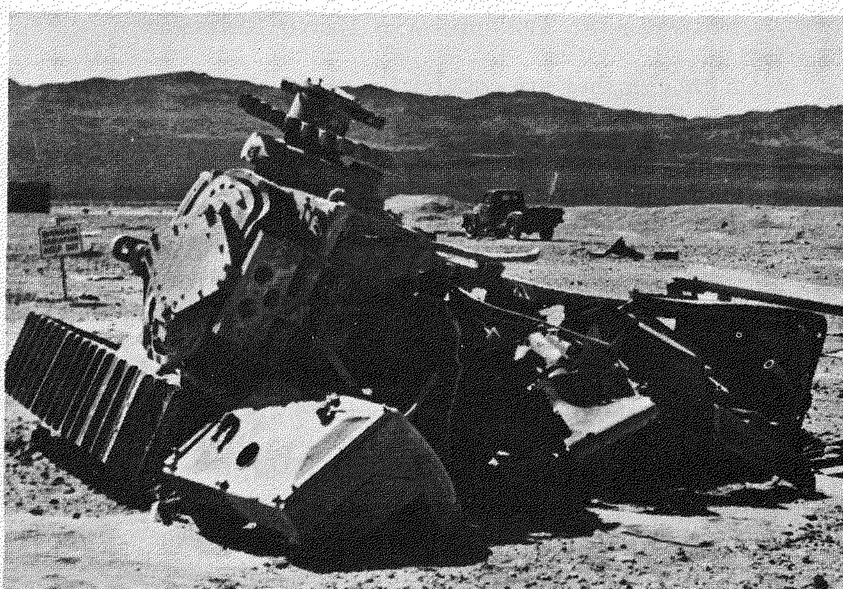

Figure 12.40b. Earth-moving equipment subjected to nuclear blast in open terrain (30 psi overpressure).

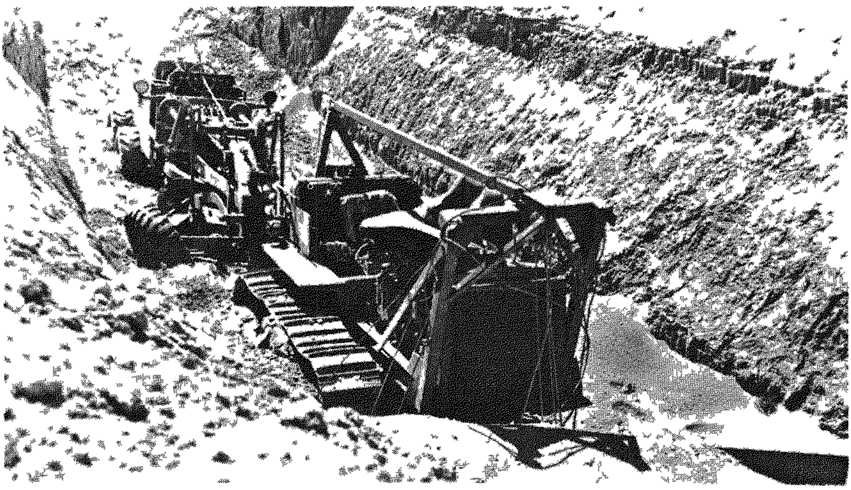

Figure 12 40c. Earth-moving equipment protected in deep trench at right angles to blast wave motion (30 psi overpressure).

12.40 The destruction caused by a nuclear explosion to two pieces of earth-moving equipment, which are largely drag-sensitive, is shown in Figs. 12.40a and b. Two similar pieces of equipment located in a deep trench, at the same distance from the explosion, are seen in Fig. 12.40c to have been essentially unharmed. It is important to mention that the main direction of the trench was at right angles to the motion of the blast wave. If the wave had been traveling in the same direction as the trench, the equipment would probably have been severely damaged. Consequently, in order to provide protection from drag forces, the orientation of the trench or earth revetment, with respect to the expected direction of the explosion, is of great importance.

Fire Protection

12.41 It was noted in Chapter VII that fires following a nuclear explosion may be started by thermal radiation and by secondary effects, such as overturning stoves and furnaces, rupture of gas pipes, and electrical short circuits. Fire-resistive construction and avoidance of fabrics and other light materials of inflammable character are essential in reducing fire damage. As shown by the tests described in § 7.82, a well-maintained house, with a yard free from inflammable rubbish, was less easily ignited by thermal radiation than a house that has not had adequate care.

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12.42 The methods of fire-resistive design and of city planning are well known and the subject need not be treated here. A special requirement is the reduction of the chances of ignition due to thermal radiation by the avoidance of trash piles and other finely divided fuel as well as combustible, especially dark colored, materials that might be exposed at windows or other openings. It has been recommended, in this connection, that all such openings be shielded against thermal radiation from all directions. The simple device of whitewashing windows will greatly reduce the transmission of thermal radiation and so decrease the probability of fires starting in the interior of the building. Other practical possibilities are the use of metal venetian blinds, reflective coatings on the window glass, and nonflammable interior pull curtains.

12.43 To judge from the experience in Japan, where the distortion by heat of exposed structural frames was considerable, it would appear desirable that steel columns and other steel members be protected from fire, especially where the contents of the building are flammable or where the building is located adjacent to flammable structures. Further, narrow firebreaks in Japan were found to be of little value. It is vital, therefore, that such firebreaks as may be provided in city planning or by demolition must be adequate for a major conflagration. A minimum width of 100 feet has been suggested.

12.44 One of the most important lessons learned from the nuclear bomb attacks on Japan is the necessity for the provision of an adequate water supply for the control of fires. In Nagasaki, the water pressure was 30 pounds per square inch at the time of the explosion, but chiefly because of numerous breaks in house service lines it soon dropped to 10 pounds per square inch. On the day following the explosion the water pressure was almost zero. This drop in the pressure contributed greatly to the extensive damage caused by fire. The experience in Hiroshima was quite similar.

SHELTERS FOR PERSONNEL

Introduction

12.45 Ideally, a shelter for personnel might be required to provide protection against air blast, ground shock, thermal radiation, initial nuclear radiation (neutrons and gamma rays), and residual nuclear radiation from fallout (external and internal sources). Such an ideal shelter is, however, virtually impossible to attain, in view of the uncertainties mentioned in § 12.2. Thus, shelter design, like that of

other types of structures, must inevitably represent a compromise involving an element of risk. For example, structures of special design (see § 12.53), located underground, can withstand blast overpressures of 100 pounds per square inch or more and can greatly attenuate nuclear radiation. With suitable ventilation systems they can also protect against fallout, as well as against chemical and biological warfare agents. But even these shelters would probably be destroyed if they were fairly close to ground zero in the event of either a surface burst or a shallow underground burst.

12.46 A variety of personnel shelters have been designed and several types have been subjected to nuclear test explosions. These shelters range from minor modifications to existing homes, for use by a small family, to special blast-resistant construction, for buildings housing fairly large groups of individuals. For houses with basements, simple, inexpensive shelters can provide additional protection that could mean survival in a nuclear attack. If there is no basement, other worthwhile measures can be taken, although they would cost more.

12.47 In the design of special shelters for the protection of personnel, underground (or earth-covered) structures are preferred, since they reduce the hazards from thermal and nuclear radiations, as well as from air blast, at a moderate cost. In the design of such shelters there are three fundamental problems which must always be considered; these are (1) the structural (engineering) design; (2) proper ventilation of the occupied areas; and (3) the provision of adequately protected entranceways.

12.48 Past experience from nuclear tests has indicated that standard engineering practices are adequate for the design of underground shelters which will withstand air blast overpressures of 100 pounds per square inch. If the particular situation is such that a smaller design pressure would appear to be adequate then, as a general rule, it will be found more economical to use a shallow underground or earth-covered shelter of a simpler type. For example, the light earth-covered or buried structures referred to in Table 6.12, would not be seriously damaged by blast overpressures of 20 to 30 pounds per square inch. More vulnerable to air blast than the structures themselves are the ducts and ventilating equipment, which bring in the air supply, and the doors, door frames, and entranceways. These consequently require special consideration.

12.49 To insure an adequate supply of uncontaminated air during

the critical period of occupancy of the shelter, the ventilating equipment and filters must remain in operating condition. This requires that intake and exhaust ducts be provided with some type of blast-arresting devices. Such devices should reduce the intensity of the blast force to the extent that the mechanical equipment and filters will not be harmed, and also that it will not be a hazard to persons in the shelter.

12.50 The entranceways to the shelter must be at least large enough to allow free access for personnel, and possibly to accommodate vehicular traffic. In addition, it is particularly important that the doors be designed to resist collapse, since the entrance of the blast wave through an opening, such as a doorway, might cause a sudden pressure rise inside the structure to a level that would be harmful to the occupants. It is always desirable that each doorway into the shelter be associated with an entranceway so placed that it will act as a blast-arresting device and also provide protection against flying missiles which might damage the door.

Family-Type (Home) Shelters

12.51 It will be recalled from Chapter IV that, even when the houses exposed to the nuclear explosions were so severely damaged, by a blast overpressure of 5 pounds per square inch, as to be rendered useless, the basements suffered little damage. Since no appreciable amount of thermal radiation would penetrate and the depth of soil outside the house would result in a considerable attenuation of the nuclear radiation, it would appear that basements offer possibilities as home shelters. Several designs for basement shelters have been tested in Nevada.

12.52 In houses without basements or where the water table makes it difficult to construct a shelter below the ground, the bathroom may be designed so that it can serve as an indoor shelter. This can be achieved by making the walls and ceiling of reinforced concrete and strengthening the floor slab (see § 4.34). The window and door openings are protected by special blast doors. A shelter of this type will provide good protection against blast, up to 5 pounds per square inch overpressure, at least, and also against thermal radiation. The degree of protection against nuclear radiation depends primarily on the thickness of the concrete walls and ceiling; the greater the thickness, the better the protection.

Underground Personnel Shelter

12.53 Where essential industrial, civic, or military activities must be maintained before, during, and after a nuclear attack, it might be desirable to have a group shelter which could be occupied continuously, although not necessarily by the same individuals. A shelter of this kind would be of the closed type and would have to be provided with a suitable ventilating system. As a result of various tests, it has been found that in "open" shelters, i. e., in shelters which are open to the entry of the blast, the peak overpressure of the blast wave is not very different from that outside. Some reduction can be achieved by suitable design of the entrance and by the use of baffles, but the general impression is that, in strategic locations, where high overpressures may be expected, open group shelters would not be adequate.

12.54 The general features of a closed, underground personnel shelter, that can accommodate some 30 individuals at a time, but can be extended to hold more, are shown in Fig. 12.54. The design is based on experience gained at various nuclear tests in which shelters of this type have withstood peak overpressures of about 100 pounds per square inch. It was also found, as expected, to produce considerable attenuation of both gamma rays and neutrons.[3]

12.55 The main shelter chamber has reinforced-concrete walls 15 inches thick; the floor slab has a thickness of 18 inches and that of the roof is 21 inches. The chamber is covered with packed earth to a depth of at least 5 feet. The entrance is by concrete steps, in two sections at right angles. Instead of extending in the direction shown in the figure, the entranceway may be turned through 180°, so as to make the whole lay-out more compact. The stairway at the ground level is closed by means of an 8-inch thick horizontal door made of structural steel and reinforced concrete. The door has four wheels and is track mounted. It is so designed that as it rolls closed it seats itself on steel bed plates on each side of the stairwell, so that the blast load is removed from the wheels and axles. A heavy jack is mounted on the underside of the ceiling of the stairwell, so that the door can be forced open in case there is an accumulation of debris in the well behind the door.

[3] The shelter described here was conceived and planned by the Federal Civil Defense Administration, with the assistance of the Army Ballistics Research Laboratory, the Army Chemical Center, and the Armed Forces Special Weapons Project. The structural design was by Ammann and Whitney, Consulting Engineers, under contract to the Federal Civil Defense Administration.

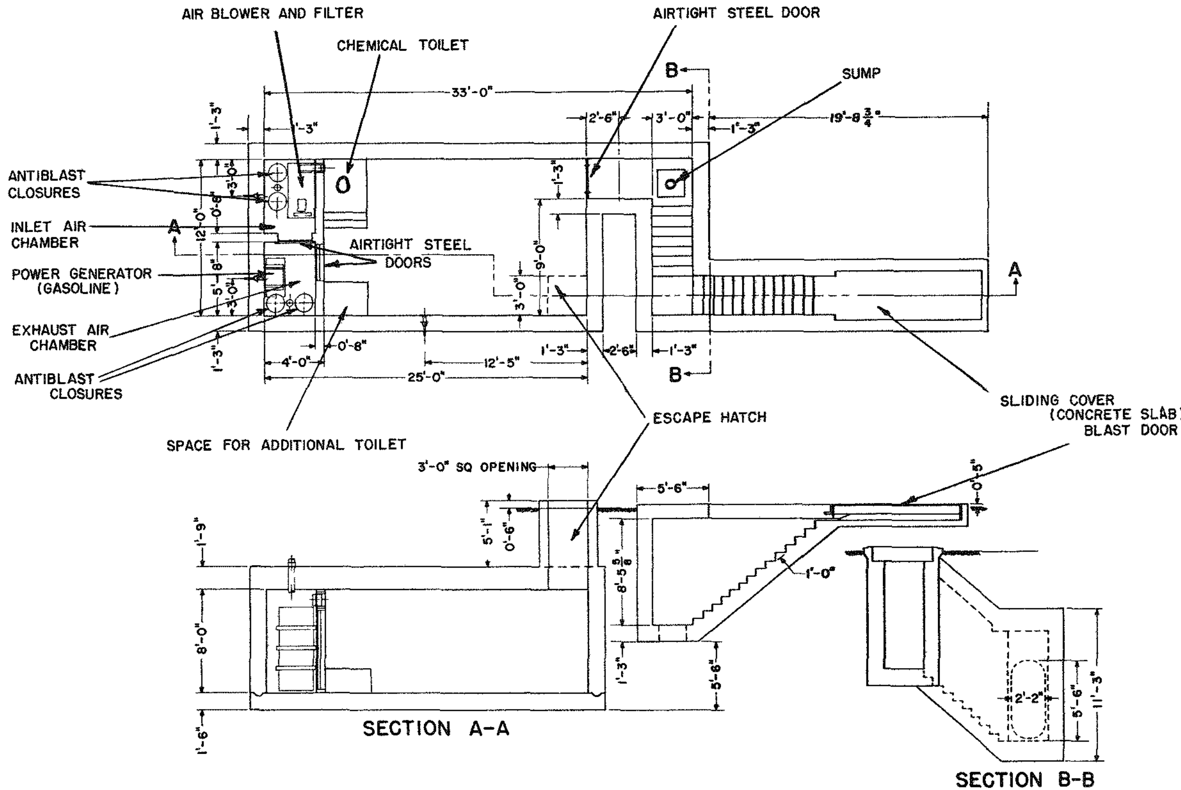

Figure 12.54. Sectional plan and section of underground personnel shelter.

12.56 Entrance to and exit from the shelter chamber is through a doorway fitted with a ½-inch steel, air tight (Navy bulkhead type) door. For emergency exit there is a 3 x 3-feet vertical escape hatch with a steel trap door. Normally the hatch is filled with washed and dried sand, but this can be run out and personnel can escape by climbing a vertical ladder in the wall.

12.57 The ventilation system for the shelter is contained in two compartments shown at the extreme left in Fig. 12.54. Air from outside enters the inlet chamber, passes through a filter, to remove particulate matter, e. g., fallout, as well as biological and chemical warfare agents, and is then blown into the shelter through ducts near the ceiling. The return air is expelled through the exhaust chamber. Both inlet and exhaust systems are fitted with special "anti-blast closures." These are so constructed that a sudden increase in the exterior pressure, due to the passage of a blast wave, will cause them to close almost instantaneously. Relief of the pressure by the negative phase of the blast wave will then open them again. The closures have been found to operate satisfactorily at peak overpressures up to at least 100 pounds per square inch.

12.58 The exhaust chamber also contains a gasoline-driven, electric generator for emergency use in the event of failure of the main power supply. An underground tank holds enough fuel for 10 days. At the other end of the shelter is a buried water tank to provide water for drinking purposes.

Emergency Shelters

12.59 From experience gained in both nuclear and conventional explosions, there is little doubt that it is, as a general rule, more hazardous in the open than inside a structure. In an emergency, therefore, the best available shelter should be taken. Many subways would provide reasonably good emergency shelter, but they are to be found in a limited number of cities. As an alternative, that is more readily available, the basement of a building should be chosen. In this connection, a fire-resistive, reinforced-concrete or steel-frame structure is to be preferred, since there is less likelihood of a large debris load on the floor over the basement. Even basements of good buildings are not, however, an adequate substitute for a well-designed shelter, since the design live loads of floors over basements are usually small in comparison with the blast overpressure to which these floors may be subjected.

12.60 In the event of a surprise attack, when there is no opportunity to take shelter, immediate action could mean the difference between life and death. The first indication of an unexpected nuclear explosion would be a sudden increase of the general illumination. It would then be imperative to avoid the instinctive tendency to look at the source of light, but rather to do everything possible to cover all exposed parts of the body. A person inside a building should immediately fall prone and crawl behind or beneath a table or desk. This will provide a partial shield against splintered glass and other flying missiles. No attempt should be made to get up until the blast wave has passed, as indicated possibly by the breaking of glass, cracking of plaster, and other signs of destruction. The sound of the explosion also signifies the arrival of the blast wave.

12.61 A person caught in the open by the sudden brightness due to a nuclear explosion, should drop to the ground while curling up to shade the bare arms, hands, neck, and face with the clothed body. Although this action may have little effect against gamma rays and neutrons, it might possibly help in reducing flash burns due to thermal radiation. The degree of protection provided will vary with the energy yield of the explosion. As stated in § 7.53, it is only with high-yield weapons that evasive action against thermal radiation is likely to be feasible. Nevertheless, there is nothing to be lost, and perhaps much to be gained, by taking such action. The curled-up position should be held until the blast wave has passed.

12.62 If shelter of some kind, no matter how minor, e. g., in a doorway, behind a tree, or in a ditch, or trench can be reached within a second, it might be possible to avoid a significant part of the initial nuclear radiation, as well as the thermal radiation. But shielding from nuclear radiation requires a considerable thickness of material and this may not be available in the open. By dropping to the ground, some advantage may be secured from the shielding provided by the terrain and surrounding objects. However, since the nuclear radiation continues to reach the earth from the atomic cloud as it rises, the protection will be only partial. Further, as a result of scattering, the radiations will come from all directions.

PROTECTION FROM FALLOUT

Passive and Active Measures

12.63 Protection against the residual nuclear radiation from fallout presents a number of difficult and involved problems. This is so

not only because the radiations are invisible, and require special instruments for their detection and measurement, but also because of the widespread and persistent character of the fallout. In the event of a surface burst of a high-yield nuclear weapon, for example, the area contaminated by the fallout could be expected to extend well beyond that in which casualties result from blast, thermal radiation, and the initial nuclear radiation. Further, whereas the other effects of a nuclear explosion are over in a few seconds, the residual radiation persists for a considerable time.

12.64 The protective measures which can be taken against sources of residual nuclear radiation fall into two main categories, namely, passive and active. Passive protection implies remaining in the contaminated area while taking all possible shelter from the gamma rays, in particular, emitted by the fission products in the fallout. As seen in Chapter IX, even the basement of a frame house can attenuate the radiation by a factor of about 10, and greater reduction is possible in a large building or in a shelter covered with several feet of earth.

12.65 There are two aspects of active protection which will be considered. One is evacuation, that is, removal of the population from a contaminated location to one that is either free from contamination or, at least, less contaminated. This action is by no means as simple as might at first appear, because it will generally involve passage, without protection, through contaminated areas. The resulting radiation exposure may thus be greater than if passive protective measures were taken without evacuation.

12.66 The other possible active procedure is decontamination after the fallout has settled. In most circumstances steps of one kind or another can be taken to decrease the amount of fallout in critical regions, e. g., roofs of houses and streets. Some of the more general methods of decontamination will be discussed later. It should be mentioned, however, that the procedures are inevitably hazardous, since they involve exposure of the operating personnel to fairly high levels of radiation.

12.67 The extent to which passive protection, evacuation, and decontamination should be practiced will depend upon the existing conditions and may vary widely from one case to another. It is impossible, therefore, to make any definite recommendations. The particular action taken must depend upon the judgment of responsible individuals, based on a knowledge of radiation intensities and various other factors, in addition to an appreciation of the characteristics of the residual nuclear radiation. A general guide to the possibilities

may perhaps be provided by the discussion of a number of different circumstances in the following sections.

Protective Action

12.68 It was recognized at the beginning of this chapter (§ 12.3) that the concept of the evacuation of populations from potential target areas was greatly complicated by the possible effects of fallout. Some aspects of the situation which must be considered before the movement of large masses of individuals can be undertaken will be outlined here. First, there is always a possibility of a sudden change in the wind pattern, so that the evacuees might be moving unwittingly into the path of the fallout. A somewhat similar circumstance might develop as the result of further explosions, at other points, after evacuation had started. In any case, accurate prediction of the fallout pattern is very difficult and requires detailed and continuous knowledge of the wind pattern over a large area and to great heights. Once the order for evacuation has been given, it would be virtually impossible to rescind it or even to change the main direction of personnel movement.

12.69 It may be that the best initial step is to take passive protective measures by seeking shelter in relatively closed structures. The gamma radiations from sources external to the body will then be appreciably attenuated. In order to prevent contaminated material from entering the body, a ventilation system with filters for removing particulate matter may be a desirable feature. However, in most buildings, sufficient air leaks through cracks or penetrates through the walls to permit satisfactory breathing even with the doors and windows closed. It is true that some of the fallout may enter at the same time, but it is believed, on the basis of the experience of the inhabitants of the Marshall Islands in the 1954 nuclear tests (§ 11.115, *et seq.*), that inhalation of the contaminated particles will not be a serious hazard.

12.70 Since the shelters may have to be occupied continuously for a period of from 2 to 7 days (or more), depending upon the level of the contamination outside, supplies of food and water will be necessary. These should be kept covered to prevent access of fallout particles. If water is available the exposed food can be washed free of contamination before being eaten (see § 12.97).

12.71 At locations relatively near to ground zero, the fallout will arrive soon after the explosion and the radiation dose rate will initial-

ly be high. It may then be necessary to wait several days before it is possible to come out of the shelter without risking a radiation dose of sufficient magnitude to cause severe injury. Leaving the shelter to evacuate the area or to start preliminary decontamination operations, will represent a calculated risk, which should not be undertaken, except in dire emergency, without the advice of a monitor familiar with the radiation situation in the surrounding area.

12.72 The farther a point in the path of the fallout is from the explosion, in the same general direction, the lower will be the initial radiation level and the shorter will be the duration of the passive protection phase. However, in any area where the contamination is at all serious, it will probably be necessary to spend the first day or two after the explosion sheltered from the residual gamma radiation. During the early stages, the activity of the fission products in the fallout is very high, but by the end of 49 hours or roughly 2 days, it will have decreased to about 1 percent of the value at 1 hour after the explosion.

12.73 It is impossible to indicate in advance at what value of the external dose rate it may be permissible to leave the shelter. Much would depend upon the next stage, e. g., evacuation or decontamination (or both), and how long it will take, as well as upon the total dose already received during the passive protection phase. The graphs given at the end of this chapter should aid in the estimation of the approximate doses that might be received under a variety of conditions. Such information is necessary before a decision can be made in any given situation.

12.74 At the beginning of this discussion it was supposed that an appreciable time elapses between the explosion and the arrival of the fallout. If, for one reason or another, there is no prior warning, the steps to be taken are essentially similar to those described above. The first action should be to seek optimum shelter, providing the maximum attenuation of the gamma radiation originating from outside sources, as quickly as possible. Speed is essential, since the radiation intensity from the fallout is extremely high soon after the explosion, but drops fairly rapidly in the course of time. After a few days, the shelter may be evacuated by a route which will involve a minimum radiation exposure.

12.75 It is appropriate to emphasize here that the presence of dangerous fallout may not be visible to the eye, and its detection requires the use of suitable instruments sensitive to nuclear radiations. It is true that some (although not all) of the fallout in the Marshall Islands, after the test shot of March 1, 1954, could be seen as a white powder or dust. But this may have been due to the light color of

the calcium oxide (or carbonate) of which the particles were mainly composed. Had the material been somewhat darker in color and the particles somewhat smaller in diameter, it is possible that the fallout would not have been seen. Continuous monitoring, with instruments, for radioactive contamination would thus appear to be essential in all areas in the vicinity of the burst.

Radiological Survey

12.76 Soon after a nuclear explosion, general radiological surveys will have to be undertaken for a number of reasons. In the first place, it may be necessary for emergency crews to enter an area that is contaminated, and the level of the radiation intensity of the area must be known. The best, i. e., least contaminated, routes into and through the area should be determined. Further, persons sheltered within a contaminated region need radiological information from outside for the purpose of planning evacuation. In addition, highly contaminated areas must be located and marked to prevent accidental entry.

12.77. The most rapid method of estimating the extent of the radiation hazard in the early stages will probably be by means of an aerial survey. The great advantage of such a survey is that it can be carried out regardless of the debris, which would make roads impassable, or of the degree of contamination. Because of their long range in air, gamma rays from fission products on the earth's surface can be detected by sensitive instruments at a height of several thousand feet. Low-flying airplanes or helicopters carrying survey meters, which measure the gamma radiation dose rate, can fly over an affected area in accordance with a predetermined pattern. The initial flights might be at an altitude of 1,500 feet or so, where the radiation intensity is reduced by a factor of nearly 100 with respect to that on the surface (see Fig. 9.122). This could be followed by flights at lower levels, if necessary, for more exact identification of contaminated areas.

12.78 From the radiation intensities recorded by the survey instruments in the aircraft at a known altitude, it is possible to obtain a rough estimate of the dose rate, e.g., in roentgens per hour, which exists at the surface of the ground or water. The exact ratio between the reading in the air and the dose rate on the surface will depend on several factors, including the nature of the terrain and the time after the detonation at which the survey is made, because of the decrease in the energy of the gamma rays from fission products. If no more specific information is available, the data in Fig. 9.122 may

be used to estimate the attenuation factor at a known altitude with reference to that on the ground.

12.79 The aerial survey is important because it can be made quickly and can provide valuable information which might be impossible to secure in any other way. Nevertheless, such a survey can serve only as a rough guide, and it must be supplemented by observations made on the ground. The information obtained from the measurements taken in the air will, however, help very greatly in planning the ground survey. In the first stages, the general extent of the contaminated area will be delineated, but later a more detailed investigation will be undertaken to determine the radiation levels at specific strategic points, to establish approximate dose-rate contours, and to locate "hot spots" of higher than average contamination.

12.80 It is important to remember that personnel performing monitoring operations will be continuously exposed to radiation, sometimes at high levels of intensity. As far as possible, they should be transported by vehicles which offer some degree of protection by attenuating the gamma radiation, e. g., by suitable shielding or distance. In order to avoid dangerous overexposure, the monitors must carry instruments which, at any time, indicate the total dose they have received. They will then know when they should return to headquarters, so that hitherto unexposed individuals may take their place and continue with the operation. If the results of a preliminary survey are available, some advance planning in this connection may be possible by using the graphs given at the end of this chapter.

Decontamination Procedures [4]

12.81 Since radioactive material cannot be destroyed, decontamination inevitably involves transfer of the source of the radiation, e. g., fallout, from a location where it is a hazard to one in which it can do little or no harm. All decontamination procedures thus have two basic aspects: first, the removal of the contaminant, and second, its disposal. Unless proper consideration is given to the latter aspect, the whole process may do little or no ultimate good. Covering the contamination without moving it, e. g., with a depth of soil, would be effectively combining both operations into one.

[4] An extensive treatment of decontamination methods and equipment will be found in the manual (TM–11–6) entitled, "Radiological Decontamination in Civil Defense," prepared by the Federal Civil Defense Administration.

12.82 Decontamination may be either gross, i. e., rough, or detailed. Gross decontamination is the rapid, partial removal or covering of contamination on a large scale. Its purpose is to reduce the radiation dose rate as quickly as possible to a point where personnel can use a piece of equipment or remain within an area for a limited period of time, at least. Subsequently, detailed decontamination, which is a lengthy and thorough process, may be carried out. As a general rule, decontamination cannot (and need not) be complete. However, the procedure should be carried to the point where the situation no longer constitutes a significant hazard under the particular conditions of use or occupation.

12.83 The decision to undertake decontamination will depend upon the circumstances, and must involve a calculated risk. Since there is always a certain degree of danger to the operating personnel, the procedure should be deferred as long as is reasonably possible, so as to take advantage of natural radioactive decay. In some cases urgent action may be necessary, and decontamination may have to be started while the radiation level is still high. Such a situation might be met by replacement of the workers with fresh, previously unexposed, crews at short intervals.

12.84 There are a few useful general principles relating to contamination and decontamination which should be borne in mind. Because of its particulate nature, the fallout will obviously tend to collect on horizontal surfaces. Such surfaces will thus be more highly contaminated than vertical surfaces. Hence, in preliminary decontamination, at least, the latter can be ignored. Most of the fallout particles can be readily removed either by washing with a stream of water or by sweeping, preferably with a vacuum cleaner to avoid inhalation of dust.

12.85 Gross decontamination can generally be performed in one or other of these ways. For smooth, e. g., painted and metallic, surfaces, wet (washing) methods may be used, but for porous materials, e. g., fabrics, brick, concrete, and stone, dry methods are to be preferred. Broadly speaking, water washing can be employed outdoors and on the exterior of vehicles, whereas vacuum sweeping is more suitable for the interiors of buildings and vehicles. Experimental tests of decontamination procedures have shown that the major portions of contaminating material can be removed by these simple methods. Only a small part of the contamination is strongly held and requires more drastic treatment, e. g., with chemicals or abrasives.[5]

[5] Contamination due to neutron-induced activity is difficult to remove, but such contamination is of importance only near the explosion center (see § 9.18).

12.86 In a city, decontamination could be carried out by hosing the roofs of buildings and the streets with strong streams of water. The radioactive material would thus be transferred to the storm sewers, where it would represent only a minor hazard. As an alternative to hosing, the dose rate inside a building could also be reduced by covering the ground surrounding the building with uncontaminated earth or by removing the top layer of the ground to a distance with a bulldozer.

12.87 It is important to note, in connection with removal of contaminated earth, for the purpose just described or to provide a means of transit, that the gamma rays from fission products can travel considerable distances through air. For example, at 3 feet above the ground, roughly 50 percent of the dose rate received in the center of a large, flat, uniformly contaminated area comes from distances greater than 25 feet away, and about 25 percent from distances more than 50 feet away. Thus, complete removal of the contaminated surface from a circle 50 feet in radius would reduce the dose rate in the center to about one-fourth of its original value. However, if the contaminated earth were not completely removed, but just pushed to the outside of the circle, the dose rate would be considerably larger than one-fourth the initial value.

12.88 It is apparent, therefore, that if transit facilities are to be provided across open country which is contaminated over a large area, bulldozing the top few inches of contaminated soil to the sides will be satisfactory only if a wide strip is cleared. Thus, if the strip is 250 feet in width, the radiation dose rate in the middle will be reduced to one-tenth of the value before clearing. A similar result may be achieved by scraping off the top layer of soil and burying it under fresh soil. Something like a foot of earth would be required to decrease the dose rate by a factor of ten.

12.89 Badly contaminated clothing, as well as rugs, curtains, and upholstered furniture, would have to be discarded and buried or stored in an isolated location. When the radioactivity has decayed to a sufficient extent, or if the initial contamination is not too serious, laundering may be effective in reducing the activity of clothing and fabrics, to permit their recovery. Thorough vacuum cleaning of furniture might be adequate in some cases, but an instrument check would be necessary before further use.

Protection of Operating Crews

12.90 All personnel entering a contaminated area, to perform survey monitoring, decontamination, or other emergency operations, should adapt their clothing to prevent the entry of dust. The main purpose of this precaution is to minimize the possibility of "beta burns" as a result of direct contact of the fallout with the skin (see § 11.94). It should be remembered, of course, that clothing offers virtually no protection against gamma radiation, and so this hazard will still exist to an undiminished extent.

12.91 For dry operations, heavy pants and shoes are recommended, as well as cotton or canvas work gloves and a tight-fitting cap. In dusty areas it is advisable that the bottoms of the pants and the ends of the sleeves (over the gloves) be tied to prevent the entry of contaminated material. A scarf around the neck would also help in this connection. After a nuclear attack, the dust may arise from rubble, disturbance of the ground, etc., and may not necessarily be radioactive. Precautions to reduce inhalation of the dust in large amounts would be desirable, in any event. Consequently, in operations in which considerable quantities of dust may be encountered, goggles and a filter mask are advisable.

12.92 For wet decontamination operations, water-repellent clothing, rubber boots, and rubber gloves will be required (Fig. 12.92). They can be cleaned with a stream of water and used several times. provided there are no breaks or tears.

12.93 In addition to taking steps to prevent radioactive material from reaching the skin, workers will need protection from excessive exposure to radiation. For this purpose, each operator should carry a self-indicating meter, sometimes called an "organizational dosimeter," to record his total radiation exposure. Various types of dosimeters have been devised, and simple and reliable instruments, that can be produced cheaply and in large numbers, are available.[6]

12.94 Survey meters for the determination of radiation intensities (dose rates) will be required in order to detect regions of high activity and for estimating permissible times of stay in a contaminated area. As a general rule, instruments which measure the dose rate of gamma radiation will be satisfactory. In addition, special instruments sensitive to beta radiations are advantageous for such purposes as detecting beta-particle emitters on the body.

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[6] For a description of dosimeters and other radiation instruments developed by the Federal Civil Defense Administration, see "Radiological Instruments for Civil Defense," TB–11–20.

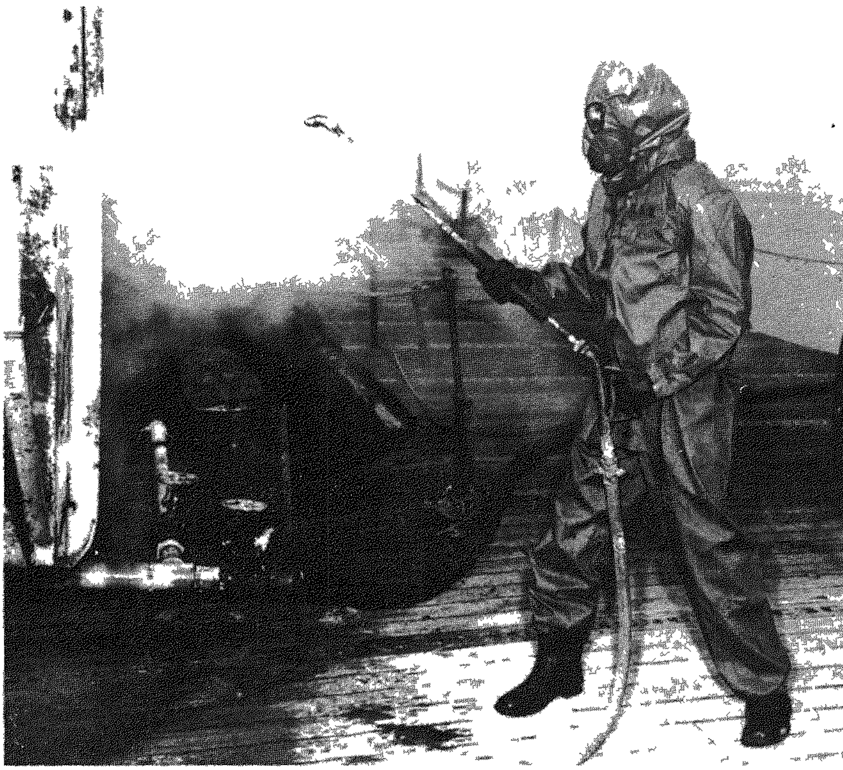

Figure 12.92 Water-repellent clothing for use in wet decontamination operations.

12.95 In connection with this aspect of personnel protection, there arises the question of the amount of nuclear radiation exposure that is permissible for those taking part in emergency operations. It is difficult, if not impossible, to supply an exact answer, for a great deal will depend upon the circumstances and the risks that must inevitably be taken.

12.96 In those phases of emergencies in which immediate action is required, it would rarely be possible to predict in advance the radiation dose that might be received as a result of such action. The consequences to the exposed individuals, would, therefore, be equally unpredictable. However, where the hazard could be estimated from available dose rate data, it might be possible to establish an approxi-

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mate guide concerning permissible radiation exposures under emergency conditions.[7]

Food and Water

12.97 Foods that are properly covered or wrapped or are stored in closed containers should suffer little or no contamination. This will be true for canned and bottled foods as well as for any articles in impervious, dust-proof wrappings. If the contamination is only on the outside, all that would be necessary for recovery purposes would be the careful removal, e. g., by washing, of any fallout particles that might have settled on the exterior of the container.[8] Even vegetables could be satisfactorily decontaminated by washing. If this were followed by removal of the outer layers, by peeling, the food should be perfectly safe for human consumption. Unprotected food products of an absorbent variety that have become contaminated should be disposed of by burial.

12.98 As for food crops grown in contaminated soil, there is not yet sufficient information available. Some radioactive isotopes may be taken up by the plant, but their nature and quantity will vary from one species to another and also, probably, with the soil characteristics (§ 9.99). All that can be stated at the present time is that plants grown in contaminated soil should be regarded with suspicion until their safety can be confirmed by means of radiological instruments.

12.99 Most sources of public water supplies are located at a considerable distance from urban centers that might be targets of a nuclear attack. Nevertheless, appreciable contamination might result if the watershed were in the range of heavy fallout from a surface burst. Other possibilities are fallout particles dropping into a river or reservoir or the explosion of a nuclear bomb near a reservoir. In most cases it is to be expected that, as a result of the operation of several factors, e. g., dilution by flow, natural decay, and removal ("adsorption") by soil, the water will be fit for consumption, on an emergency basis, at least, except perhaps for a limited time immediately following the nuclear explosion. In any event, where the water from a reservoir is subjected to regular treatment, including coagu-

[7] See, for example, "Emergency Exposures to Nuclear Radiation," Federal Civil Defense Administration Technical Bulletin (TB-18-1).

[8] Food could become contaminated even inside containers due to neutron-induced activity, but this is not likely to be important in locations where the packaged foodstuffs have survived the nuclear explosion intact (§ 9.25).

lation, sedimentation, and filtration, it is probable that much of the radioactive material would be removed.

12.100 Because soil has the ability to take up and retain certain elements by the process of "adsorption," underground sources of water will generally be free from contamination. For the same reason, moderately deep wells, even under contaminated ground, can be used as safe sources of drinking water, provided, as is almost invariably the case, there is no direct drainage from the surface into the well.

12.101 In some cities, water is taken directly from a river and merely chlorinated before being supplied for domestic purposes. The water may be unfit for consumption for several days, but, as a result of dilution and natural decay, the degree of contamination will decrease with time. It would be necessary, in cases of this kind, to subject the water to examination for radioactivity and to withhold the supply until it is reasonably safe. Assuming the contamination is due to fission products, the acceptable total beta (or gamma) activities under emergency conditions, for 10 and 30 day periods, respectively, are given in Table 12.101. Thus, if it is anticipated that the water will have to be used regularly for a period of 30 days, the maximum permissible activity is 3×10^{-2} microcuries per cubic centimeter (see § 9.125, *et seq.*). On the other hand, if it appears that the period will be shorter, water of proportionately higher activity may be consumed in an emergency.

TABLE 12.101

ACCEPTABLE EMERGENCY BETA (OR GAMMA) ACTIVITIES IN DRINKING WATER

	Activity	
Consumption period (days)	*Microcuries per cubic centimeter*	*Disintegrations per second per cubic centimeter*
10	9×10^{-2}	3×10^{3}
30	3×10^{-2}	1×10^{3}

12.102 The emergency limits for alpha particle emitters, such as uranium and plutonium, in water are appreciably less than those given in Table 12.101. However, it is expected that only in rare circumstances would these elements represent a contamination hazard in drinking water.

12.103 If the regular water supply is not usually subjected to any treatment other than chlorination, and an alternative source is not available, consideration should be given to the provision of ion-exchange columns (or beds) for emergency use in case of contamination.

Home water softeners might serve the same purpose on a small scale. Incidentally, the water contained in a domestic hot-water heater could serve as an emergency supply, provided it can be removed without admitting contaminated water.

12.104 In hospitals and on ships, sufficient water for emergency purposes could be obtained by distillation. It was found after the nuclear tests at Bikini in 1946, for example, that contaminated sea water when distilled was perfectly safe for drinking purposes; the radioactive material remained behind in the residual scale and brine. It should be emphasized, however, that mere boiling of water contaminated with fallout is of absolutely no value as regards removal of the radioactivity.

Radiation Doses and Times in Contaminated Areas

12.105 For the planning of defensive action, either active or passive, or of survey operations in an area contaminated with fission products, it is necessary either to make some estimate of the permissible time of stay for a prescribed dose or to determine the dose that would be received in a certain time period. The basic equations and the related graphs (Figs. 9.8 and 9.12) were given in Chapter IX, but the same results may be expressed in an alternative form that is more convenient for many purposes.[9]

12.106 If the radiation dose rate from fission products is known at a certain time in a given location, Fig. 12.106 may be used to determine the dose rate at any other time at the same location, assuming there has been no change in the fallout other than natural radioactive decay. The same nomogram can be utilized, alternatively, to determine the time after the explosion at which the dose rate will have attained a specified value. If there has been any change in the situation, either by further contamination or by decontamination, in the period between the two times concerned, the results obtained from Fig. 12.106 will not be valid.

12.107 To determine the total radiation dose received during a specified time of stay in a contaminated area, if the dose rate in that area at any given time is known, use is made of Fig. 12.107, in conjunction with Fig. 12.106. The chart may also be employed to evaluate the time when a particular operation may be commenced in order not to exceed a certain total radiation dose.

[9] Devices of the slide-rule type, referred to in the footnote to § 9.11, are very useful for making rapid calculations of the kind described here.

12.198 Another type of calculation of radiation dose in a contaminated area is based on a knowledge of the dose rate at the time of entry into that area. The procedure described in the examples facing Fig. 12.107, which also require the use of Fig. 12.106, may then be applied to determine either the total dose received in a specified time of stay or the time required to accumulate a given dose of radiation. The calculation may, however, be simplified by means of Fig. 12.108, which avoids the necessity for evaluating the 1-hour reference dose rate, provided the dose rate at the time of entry into the contaminated area is known.

12.109 If the whole of the fallout reached a given area within a short time, Fig. 12.108 could be used to determine how the total radiation dose received by inhabitants of that area would increase with time, assuming no protection. For example, suppose the fallout arrived at 6 hours after the explosion and the dose rate at that time was R roentgens per hour; the total dose received would be $8R$ roentgens in 1 day, $11R$ roentgens in 2 days, and $13R$ roentgens in 5 days.

12.110. It is evident that the first day or so after the explosion is the most hazardous as far as the exposure to residual nuclear radiation from fallout is concerned. Although the particular values given above apply to the case specified, i. e., complete fallout arrival 6 hours after the explosion, the general conclusions to be drawn are true in all cases. The radiation doses that would be received during the first day or two are considerably greater than on subsequent days. Consequently, it is in the early stages following the explosion that protection from fallout is most important.

The nomogram shows the relationship between the dose rate at any time after the explosion and the 1-hour reference value (R_1). If the dose rate at any time is known, that at any other time can be derived from the figure. Alternatively, the time after the explosion at which a specific dose rate is attained can be determined.

Example

Given: The radiation dose rate due to fallout at a certain location is 8 roentgens per hour at 6 hours after a nuclear explosion.

Find: (*a*) The dose rate at 24 hours after the burst.

(*b*) The time after the explosion at which the dose rate is 1 roentgen per hour.

Solution: By means of a ruler (or straight edge) join the point representing 8 roentgens per hour on the left scale to the time 6 hours on the right scale. The straight line intersects the middle scale at 70 roentgens per hour; this is the 1-hour reference value of the dose rate (R_1).

(*a*) Using the straight edge, connect this reference point (70 r/hr) with that representing 24 hours after the explosion on the right scale, and extend the line to read the corresponding dose rate on the left scale, i. e., 1.5 roentgens per hour. *Answer*

(*b*) Extend the straight line joining the dose rate of 1 roentgen per hour on the left scale to the reference value of 70 roentgens per hour on the middle scale out to the right scale. This is intersected at 34 hours after the explosion. *Answer*

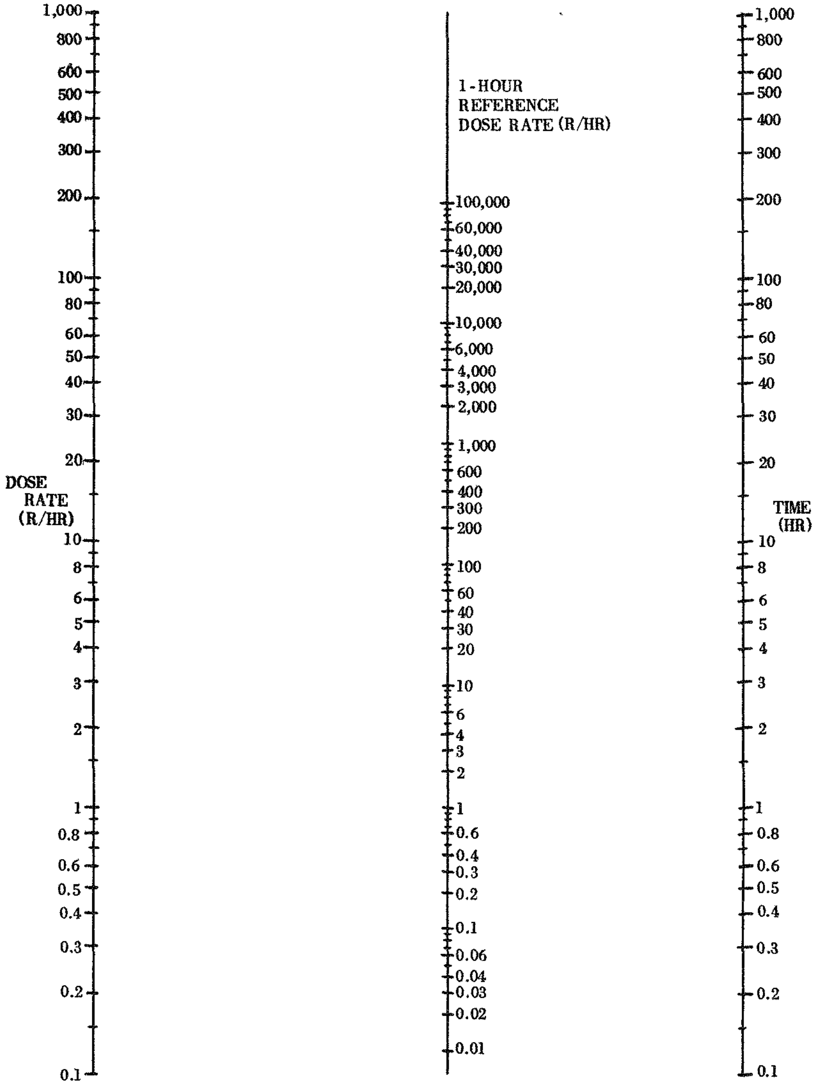

Figure 12.106. Calculation of dose rates from fission products in the fallout.

From the chart, the total radiation dose received from fission product fallout during any specified stay in a contaminated area can be determined if the dose rate at some definite time after the explosion is known. Alternatively, the time can be calculated for commencing an operation requiring a specified stay and a prescribed total radiation dose.

Example

Given: The dose rate at 4 hours after a nuclear explosion is 6 roentgens per hour.

Find: (*a*) The total dose received during a period of 2 hours commencing at 6 hours after the explosion.

(*b*) The time after the explosion when an operation requiring a stay of 5 hours can be started if the total dose is to be 4 roentgens.

Solution: The first step is to determine the 1-hour reference dose rate (R_1). From Fig. 12.106, a straight line connecting 6 roentgens per hour on the left scale with 4 hours on the right scale intersects the middle scale at 32 roentgens per hour; this is the value of R_1.

(*a*) Enter Fig. 12.107 at 6 hours after the explosion (vertical scale) and move across to the curve representing a time of stay of 2 hours. The corresponding reading on the horizontal scale, which gives the multiplying factor to convert R_1 to the required total dose, is seen to be 0.19. Hence, the total dose received is

$$0.19 \times 32 = 6.1 \text{ roentgens.} \quad \textit{Answer}$$

(*b*) Since the total dose is given as 4 roentgens and R_1 is 32 roentgens per hour, the multiplying factor is $4/32 = 0.125$. Entering Fig. 12.107 at this point on the horizontal scale and moving upward until the (interpolated) curve for 5 hours stay is reached, the corresponding reading on the vertical scale, giving the time after the explosion, is seen to be 19 hours. *Answer*

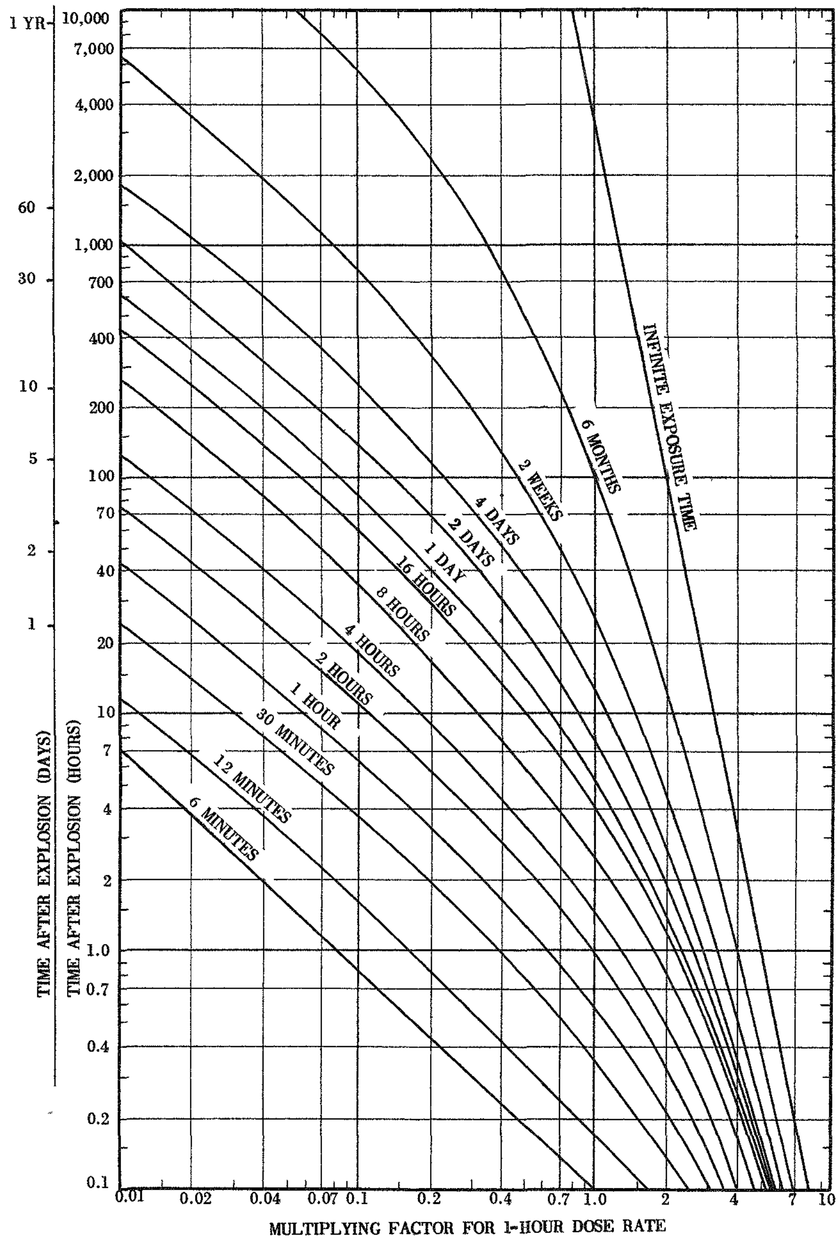

Figure 12.107. Total (accumulated) radiation dose due to fallout in a contaminated area based on 1-hour reference dose rate.

From the chart, the total radiation dose received from fission product fallout during any specified stay in a contaminated area can be determined if the dose rate at the time of entry into the area is known. Alternatively, the time of stay may be evaluated if the total dose is prescribed.

Example

Given: Upon entering a contaminated area at 12 hours after a nuclear explosion the dose rate is 5 roentgens per hour.

Find: (*a*) The total radiation dose received for a stay of 2 hours.
(*b*) The time of stay for a total dose of 10 roentgens.

Solution: (*a*) Start at the point on Fig. 12.108 representing 12 hours after the explosion on the vertical scale and move across to the curve representing a time of stay of 2 hours. The multiplying factor for the dose rate at the time of entry, as read from the horizontal scale, is seen to be 1.9. Hence, the total dose received is

$$1.9 \times 5 = 9.5 \text{ roentgens.} \quad \textit{Answer}$$

(*b*) The total dose is 10 roentgens and the dose rate at the time of entry is 5 roentgens per hour; hence, the multiplying factor is $10/5 = 2.0$. Enter Fig. 12.108 at the point corresponding to 2.0 on the horizontal scale and move upward to meet a horizontal line which starts from the point representing 12 hours after the explosion on the vertical scale. The two lines are seen to intersect at a point indicating a time of stay of about 2⅓ hours. *Answer*

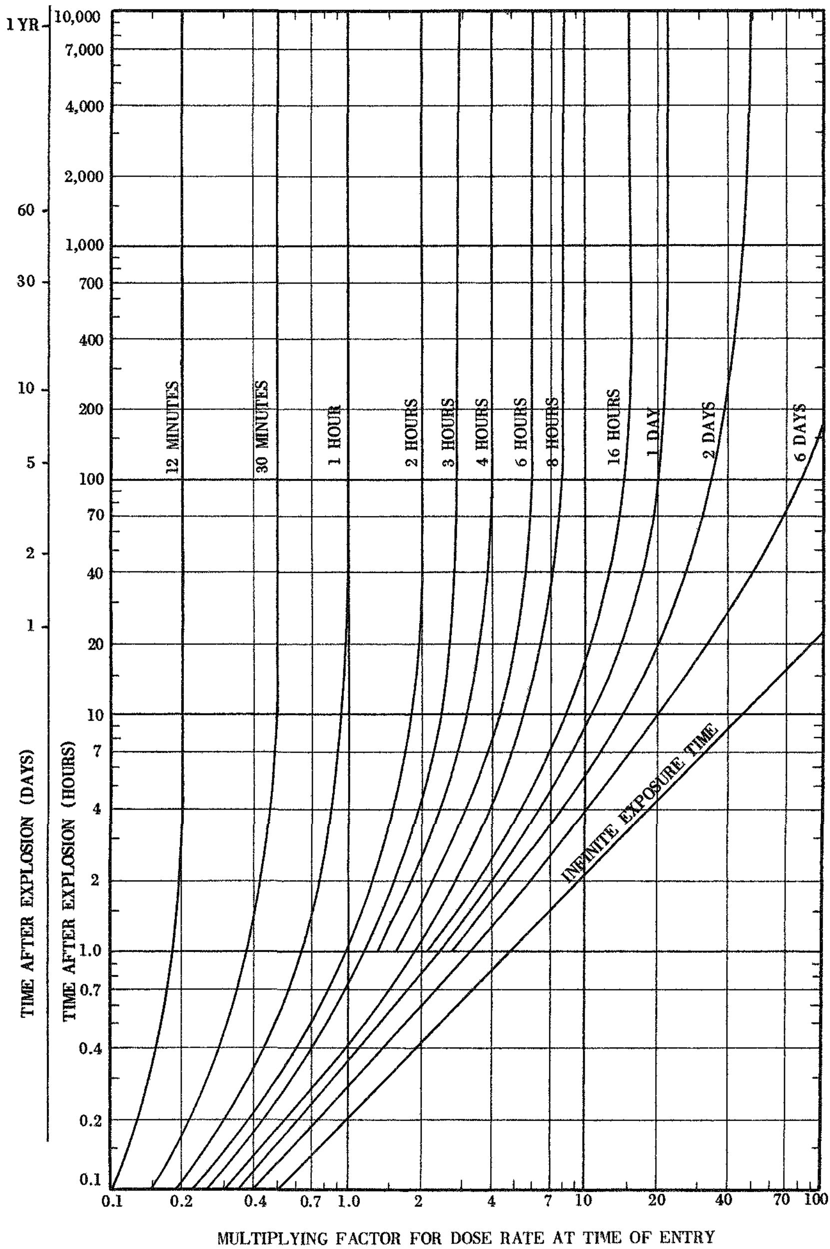

Figure 12.108. Total (accumulated) radiation dose due to fallout in a contaminated area based on dose rate at time of entry.

for the design and improvement of nuclear (or atomic) weapons and to study the phenomena and effects associated with nuclear (or atomic) explosions. Many of the data presented in this book are based on measurements and observations made at such tests. The code names and some information concerning all the tests performed through 1956 by the U. S. Atomic Energy Commission are given in the appended table.

SUMMARY OF NUCLEAR TESTS

Date	Code name	Location	Total No.	Air drops	Tower	Surface	Underground	Underwater
1945	TRINITY	New Mexico	1		1			
1946	CROSSROADS	Pacific	2	1				1
1948	SANDSTONE	Pacific	3		3			
1951	RANGER	Nevada	5	5				
1951	GREENHOUSE	Pacific	4		4			
1951	BUSTER	Nevada	5	4	1			
1951	JANGLE	Nevada	2			1	1	
1952	TUMBLER	Nevada	4	4				
1952	SNAPPER	Nevada	4		4			
1952	IVY	Pacific	2	1		1		
1953	UPSHOT	Nevada	9	2	7			
1953	KNOTHOLE	Nevada	2	2				
1954	CASTLE	Pacific						
1955	TEAPOT	Nevada	14	3	10		1	
1955	WIGWAM	At sea	1					1
1956	REDWING	Pacific						

NUCLEAR WEAPON (OR BOMB): A general name given to any weapon in which the explosion results from the energy released by reactions involving atomic nuclei, either fission or fusion or both. Thus, the A (or atomic) bomb and the H (or hydrogen) bomb are both nuclear weapons. It would be equally true to call them atomic weapons, since it is the energy of atomic nuclei that is involved in each case. However, it has become more-or-less customary, although it is not strictly accurate, to refer to weapons in which all the energy results from fission as A bombs or atomic bombs. In order to make a distinction, those weapons in which part, at least, of the energy results from thermonuclear (fusion) reactions among the isotopes of hydrogen have been called H bombs or hydrogen bombs.

NUCLEUS (OR ATOMIC NUCLEUS): The small, central, positively charged region of an atom which carries essentially all the mass. Except for the nucleus of ordinary (light) hydrogen, which is a single proton, all atomic nuclei contain both protons and neutrons. The number of protons determines the total positive charge, or *atomic number;* this is the same for all the atomic nuclei of a given chemical element. The total number of neutrons and protons, called the *mass number*, is closely related to the mass (or weight) of the atom. The nuclei of *isotopes* of a given element contain the same number of protons, but different numbers of neutrons. They thus have the same atomic number, and so are the same element, but they have different mass numbers (and masses). The nuclear properties, e. g., radioactivity, fission, neutron capture, etc., of an isotope of a given element are determined by both

the number of neutrons and the number of protons. See *Atom, Element, Isotope, Neutron, Proton.*

OVERPRESSURE: The transient pressure, usually expressed in pounds per square inch, exceeding the ambient pressure, manifested in the shock (or blast) wave from an explosion. The variation of the overpressure with time depends on the energy yield of the explosion, the distance from the point of burst, and the medium in which the weapon is detonated. The *peak overpressure* is the maximum value of the overpressure at a given location and is generally experienced at the instant the shock (or blast) wave reaches that location. See *Shock wave.*

PACIFIC PROVING GROUNDS: See *Eniwetok Proving Grounds.*

PLASTIC RANGE: The stress range in which a material will not fail when subjected to the action of a force, but will not recover completely, so that a permanent deformation results, when the force is removed. *Plastic deformation* refers to dimensional changes occurring within the plastic range. See *Elastic range.*

PLUME: See *Column.*

POSITIVE PHASE: See *Shock wave.*

PROTON: A particle of mass (approximately) unity carrying a unit positive charge; it is identical physically with the nucleus of the ordinary (light) hydrogen atom. All atomic nuclei contain protons. See *Nucleus.*

RAD: A unit of absorbed dose of radiation; it represents the absorption of 100 ergs of nuclear (or ionizing) radiation per gram of the absorbing material or tissue.

RADIATION: See *Nuclear radiation, Thermal radiation.*

RADIATION SYNDROME: See *Syndrome.*

RADIOACTIVITY: The spontaneous emission of radiation, generally alpha or beta particles, often accompanied by gamma rays, from the nuclei of an (unstable) isotope. As a result of this emission the radioactive isotope is converted (or decays) into the isotope of a different element which may (or may not) also be radioactive. Ultimately, as a result of one or more stages of radioactive decay, a stable (nonradioactive) end product is formed.

RBE (OR RELATIVE BIOLOGICAL EFFECTIVENESS): The ratio of the number of rads of gamma (or X) radiation of a certain energy which will produce a specified biological effect to the number of rads of another radiation required to produce the same effect is the RBE of this latter radiation.

REFLECTED PRESSURE: The total pressure which results instantaneously at the surface when a shock (or blast) wave traveling in one medium strikes another medium, e. g., at the instant when the front of a blast wave in air strikes the surface of an object or structure.

REFLECTION FACTOR: The ratio of the total (reflected) pressure to the incident pressure when a shock (or blast) wave traveling in one medium strikes another.

REM: A unit of biological dose of radiation; the name is derived from the initial letters of the term "roentgen equivalent man (or mammal)." The number of rems of radiation is equal to the number of rads absorbed multiplied by the RBE of the given radiation (for a specified effect). See *Rad, RBE.*

REP: A unit of absorbed dose of radiation; the name is derived from the initial letters of the term "roentgen equivalent physical." Basically, the rep is

intended to express the amount of energy absorbed per gram of soft tissue as a result of exposure to 1 roentgen of gamma (or X) radiation. This is estimated to be about 97 ergs, although the actual value depends on certain experimental data which are not precisely known. The rep is thus defined, in general, as the dose of any ionizing radiation which results in the absorption of 97 ergs of energy per gram of soft tissue. For soft tissue, the rep and the rad are essentially the same. See *Rad, Roentgen.*

RESIDUAL NUCLEAR RADIATION: Nuclear radiation, chiefly beta particles and gamma rays, which persists for some time following a nuclear (or atomic) explosion. The radiation is emitted mainly by the fission products and other bomb residues in the fallout, and to some extent by earth and water constituents, and other materials, in which radioactivity has been induced by the capture of neutrons. See *Fallout, Induced radioactivity, Initial nuclear radiation.*

ROENTGEN: A unit of exposure dose of gamma (or X) radiation. It is defined precisely as the quantity of gamma (or X) radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying one electrostatic unit quantity of electricity of either sign. From the accepted value for the energy lost by an electron in producing a positive-negative ion pair in air, it is estimated that 1 roentgen of gamma (or X) radiation, would result in the absorption of 87 ergs of energy per gram of air.

SCALING LAW: A mathematical relationship which permits the effects of a nuclear (or atomic) explosion of given energy yield to be determined as a function of distance from the explosion (or from ground zero), provided the corresponding effect is known as a function of distance for a reference explosion, e. g., of 1-kiloton energy yield. See *Blast scaling law, Cube root law.*

SCATTERING: The diversion of radiation, either thermal or nuclear, from its original path as a result of interactions (or collisions) with atoms, molecules, or larger particles in the atmosphere or other medium between the source of the radiations, e. g., a nuclear (or atomic) explosion, and a point at some distance away. As a result of scattering, radiations (especially gamma rays and neutrons) will be received at such a point from many directions instead of only from the direction of the source.

SHEAR WALL: A wall (or partition) designed to take a load in the direction of the plane of the wall, as distinct from lateral loads perpendicular to the wall. Shear walls may be designed to take lateral loads as well. See *Bearing wall.*

SHIELDING: Any material or obstruction which absorbs radiation and thus tends to protect personnel or materials from the effects of a nuclear (or atomic) explosion. A moderately thick layer of any opaque material will provide satisfactory shielding from thermal radiation, but a considerable thickness of material of high density may be needed for nuclear radiation shielding.

SHOCK FRONT (OR PRESSURE FRONT): The fairly sharp boundary between the pressure disturbance created by an explosion (in air, water, or earth) and the ambient atmosphere, water, or earth, respectively. It constitutes the front of the shock (or blast) wave.

SHOCK WAVE: A continuously propagated pressure pulse (or wave) in the surrounding medium which may be air, water, or earth, initiated by the

expansion of the hot gases produced in an explosion. A shock wave in air is generally referred to as a blast wave, because it is similar to (and is accompanied by) strong, but transient, winds. The duration of a shock (or blast) wave is distinguished by two phases. First there is the *positive* (or *compression*) *phase* during which the pressure rises very sharply to a value that is higher than ambient and then decreases rapidly to the ambient pressure. The duration of the positive phase increases and the maximum (peak) pressure decreases with increasing distance from an explosion of given energy yield. In the second phase, the *negative* (or *suction*) *phase*, the pressure falls below ambient and then returns to the ambient value. The duration of the negative phase is approximately constant throughout the blast wave history and may be several times the duration of the positive phase. Deviations from the ambient pressure during the negative phase are never large and they decrease with increasing distance from the explosion. See *Overpressure.*

SLANT RANGE: The distance from a given location, usually on the earth's surface, to the point at which the explosion occurred.

SLICK: The trace of an advancing shock wave seen on the surface of reasonably calm water, as a circle of rapidly increasing size apparently whiter than the surrounding water. It is observed, in particular, following an underwater explosion.

SPRAY DOME: See *Dome.*

SUBSURFACE BURST: See *Underground burst, Underwater burst.*

SUPERCRITICAL: A term used to describe the state of a given fission system when the quantity of fissionable material is greater than the critical mass under the existing conditions. A highly supercritical system is essential for the production of energy at a very rapid rate so that an explosion may occur. See *Critical mass.*

SURFACE BURST: The explosion of a nuclear (or atomic) weapon at the surface of the land or water or at a height above the surface less than the radius of the fireball at maximum luminosity (in the second thermal pulse). An explosion in which the bomb is detonated actually on the surface is called a *contact surface burst* or a *true surface burst.* See *Air burst.*

SURFACE ZERO: See *Ground zero.*

SURGE (OR SURGE PHENOMENA): See *Base surge.*

SURVEY METER: A portable instrument, such as a Geiger counter or ionization chamber, used to detect nuclear radiation and to measure the dose rate. See *Monitoring.*

SYNDROME, RADIATION: The complex of symptoms characterizing the disease known as *radiation sickness*, resulting from excessive exposure of the whole (or a large part) of the body to ionizing radiation. The earliest of these symptoms are nausea, vomiting, and diarrhea, which may be followed by loss of hair (epilation), hemorrhage, inflammation of the mouth and throat, and general loss of energy. In severe cases, where the radiation exposure has been relatively large, death may occur within two to four weeks. Those who survive 6 weeks after the receipt of a single dose of radiation may generally be expected to recover.

TESTS: See *Nuclear tests.*

THERMAL ENERGY: The energy emitted from the ball of fire as thermal radiation. The total amount of thermal energy received per unit area at a specified distance from a nuclear (or atomic) explosion is generally expressed

in terms of calories per square centimeter. See *Thermal radiation, Transmittance.*

THERMAL ENERGY YIELD (OR THERMAL YIELD) : The part of the total energy yield of the nuclear (or atomic) explosion which is radiated as thermal energy. As a general rule, the thermal energy is one-third of the total energy of the explosion. It may be expressed in calories, ergs, or in terms of the TNT equivalent.

THERMAL RADIATION: Electromagnetic radiation emitted (in two pulses) from the ball of fire as a consequence of its very high temperature; it consists essentially of ultraviolet, visible, and infrared radiations. In the early stages (first pulse), when the temperature of the fireball is extremely high, the ultraviolet radiation predominates; in the second pulse, the temperatures are lower and most of the thermal radiation lies in the visible and infrared regions of the spectrum.

THERMONUCLEAR: An adjective referring to the process (or processes) in which very high temperatures are used to bring about the fusion of light nuclei, such as those of the hydrogen isotopes, deuterium and tritium, with the accompanying liberation of energy. A *thermonuclear bomb* is a weapon in which part of the explosion energy results from thermonuclear fusion reactions. The high temperatures required are obtained by means of a fission explosion. See *Fusion.*

THRESHOLD DETECTOR: An element (or isotope) in which radioactivity is induced only by the capture of neutrons having energies in excess of a certain threshold value characteristic of the element (or isotope). Threshold detectors are used to determine the neutron spectrum from a nuclear (or atomic) explosion, i. e., the numbers of neutrons in various energy ranges.

TNT EQUIVALENT: A measure of the energy released in the detonation of a nuclear (or atomic) weapon, or in the explosion of a given quantity of fissionable material, expressed in terms of the quantity of TNT which would release the same amount of energy when exploded. The TNT equivalent is usually stated in kilotons or megatons. The basis of the TNT equivalence is that the explosion of 1 ton of TNT releases 10^9 calories of energy. See *Kiloton, Megaton, Yield.*

TRANSMITTANCE (ATMOSPHERIC) : The fraction (or percentage) of the thermal energy received at a given location after passage through the atmosphere relative to that which would have been received at the same location if no atmosphere were present.

TRIPLE POINT: The intersection of the incident, reflected, and fused (or Mach) shock fronts accompanying an air burst. The height of the triple point above the surface, i. e., the height of the Mach stem, increases with increasing distance from a given explosion. See *Mach stem.*

TRITIUM: A radioactive isotope of hydrogen, having a mass of 3 units; it is produced in nuclear reactors by the action of neutrons on lithium nuclei.

TRUE SURFACE BURST: See *Surface burst.*

$2W$ CONCEPT: The concept that the explosion of a weapon of energy yield W on the earth's surface produces blast phenomena identical to those produced by a weapon of twice the yield, i. e., $2W$, burst in free air, i. e., away from any reflecting surface.

UNDERGROUND BURST: The explosion of a nuclear (or atomic) weapon with its center beneath the surface of the ground.

UNDERWATER BURST: The explosion of a nuclear (or atomic) weapon with its center beneath the surface of the water.

VISIBILITY RANGE (OR VISIBILITY): The horizontal distance (in miles) at which a large dark object can just be seen against the horizon sky in daylight. The visibility is related to the clarity of the atmosphere, ranging from more than 30 miles for an exceptionally clear atmosphere to less than a mile for dense haze or fog.

WEAPON, ATOMIC (OR NUCLEAR): See *Nuclear weapon.*

WILSON CLOUD CHAMBER: See *Condensation cloud.*

YIELD (OR ENERGY YIELD): The total effective energy released in a nuclear (or atomic) explosion. It is usually expressed in terms of the equivalent tonnage of TNT required to produce the same energy release in an explosion. The total energy yield is manifested as nuclear radiation, thermal radiation, and shock (and blast) energy, the actual distribution being dependent upon the medium in which the explosion occurs (primarily) and also upon the type of weapon and the time after detonation.

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